IGOR BONINSENHA

OPTIMIZATION OF ECONOMIC INDICATORS OF RAINFED AND IRRIGATED AGRICULTURE IN WESTERN BAHIA USING LINEAR PROGRAMMING AND HYDROCLIMATIC FORECAST

Dissertation submitted to the Agricultural Engineering Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Magister Scientiae*.

Adviser: Everardo Chartuni Mantovani

Co-advisers: Marcos Heil Costa
Aziz Galvão da Silva Júnior

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To Iraci Maria Vaneli da Silva and
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To God.

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BIOGRAPHY

Igor Boninsenha, son of Antonio Fabricio Arrivabene Boninsenha and Beatriz Martins da Silva Boninsenha, was born in Marilândia, ES, Brazil, on May 25, 1996.

In 2011, he began his academic journey as Agricultural Technician at the Espirito Santo’s Federal Institute, in Colatina, ES, Brazil, graduating in 2013.

In 2014 he started the Agronomy course at the Federal University of Viçosa, where he obtained the title of Agricultural Engineer in January 2019.

Also in 2019, he joined the Graduate Program in Agricultural Engineering at the Federal University of Viçosa, focus on Water and Environmental Resources, at master's level, completed in February 2021.

ABSTRACT

BONINSENHA, Igor, M.Sc., Universidade Federal de Viçosa, February, 2021. **Optimization of Economic Indicators of Rainfed and Irrigated Agriculture in Western Bahia Using Linear Programming and Hydroclimatic Forecast**. Adviser: Everardo Chartuni Mantovani. Co-advisers: Marcos Heil Costa and Aziz Galvão da Silva Júnior.

Divided into two chapters, this dissertation presents a linear programming model to optimize agricultural activity for selected regions in Western Bahia considering the hydroclimatic forecasting model and the indicators and possible economic gains from the adoption of the rainy season onset forecast in the region. In the first chapter, the application of the linear programming model at different levels of water use demonstrated that the model could provide information to optimize agricultural activity in the region, especially in scenarios of delay or reduction in rainfall, in addition to being able to guide governance actions by water resources. The second chapter presents the economic indicators of agricultural activity for the Western Bahia, showing that the equivalence of an irrigated hectare occurs on average in 3.90 hectares of rainfed land and that the adoption of the forecast model for the beginning of the rainy season can generate increases up to 30% in revenue generation from agricultural activity.

Keywords: Water resources governance. Agricultural Production Value. Water productivity.

RESUMO

BONINSENHA, Igor, M.Sc., Universidade Federal de Viçosa, fevereiro de 2021. **Otimização dos Indicadores Econômicos da Agricultura Irrigada e de Sequeiro no Oeste da Bahia Utilizando Programação Linear e Previsão Hidroclimática**. Orientador: Everardo Chartuni Mantovani. Coorientadores: Marcos Heil Costa e Aziz Galvão da Silva Júnior.

Dividida em dois capítulos, esta dissertação apresenta um modelo de programação linear para otimização da atividade agrícola para regiões selecionadas no Oeste da Bahia considerando o modelo de previsão hidroclimática e os indicadores e possíveis ganhos econômicos da adoção do sistema de previsão do início da estação chuvosa na região. No primeiro capítulo a aplicação do modelo de programação linear em diferentes níveis de uso de água demonstrou que o modelo pode fornecer informações para otimizar a atividade agrícola na região, especialmente em cenários de atraso ou redução de chuvas, além de poder guiar ações de governança dos recursos hídricos. O segundo capítulo apresenta os indicadores econômicos da atividade agrícola para o Oeste da Bahia, sendo demonstrado que a equivalência de um hectare irrigado se dá em média em 3.90 hectares de sequeiro e que a adoção do modelo de previsão de início da estação chuvosa pode gerar incrementos de até 30% na geração de receita da atividade agrícola.

Palavras-chave: Governança dos recursos hídricos. Valor Bruto da Produção Agrícola. Produtividade da água.

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LIST OF ACRONYMS AND ABBREVIATIONS

ANOVA	Analysis of variance
C	Unitary production cost value
CONAB	National Supply Company
CTA	Total capacity of water in soil
CWD	Crop water demand
CwdI	Crop water demand in irrigated area
CwdR	Crop water demand in rainfed area
DECSD	Decisão São Desidério Farm
DRB MOR	Decisão Rio Branco e Morena Farm
DV	Decision variables
ETa	Actual evapotranspiration
ETcP	Potential crop evapotranspiration
ETo	Reference evapotranspiration
ETx	Maximum evapotranspiration
GDP	Gross domestic product
GP	Gross profit
Ia	Irrigated area
IAE	Irrigated area equivalence
IBGE	Brazilian Statistics Institute.
INMET	National Institute of Meteorology
Kc	Crop coefficient
Kl	Location coefficient
Ks	Water availability coefficient
Ky	Yield response factor
L	Labor
LAA	Current soil’s water depth
LPM	Linear programming model
LSD	Least significant difference
M	Machinery
MATOPIBA	Brazilian states of Maranhão, Piauí, Tocantins, and Bahia

NB	Net benefit
OF	Objective function
Q25	Frist quartile of data distribution
Q75	Third quartile of data distribution
R	Unitary revenue value
Ra	Rainfed area
Res	Resources
REV	Sum of revenues
SC	Sum of costs
WBI	Total water inputs
WP	Water productivity
WPr	Water profitability
Ya	Actual crop yield
Yx	Maximum crop yield

SUMMARY

1. A LINEAR PROGRAMMING MODEL FOR THE OPERATIONAL OPTIMIZATION OF AGRICULTURAL ACTIVITY CONSIDERING THE HYDROCLIMATIC FORECAST, CASE STUDIES FOR WESTERN BAHIA.

1.1. ABSTRACT

The rational use of water resources depends directly on the availability of information. Especially in a region of large development of irrigated agriculture, such as Western Bahia, decision making related to water resources management must be made to avoid water use conflicts. Integrating information provided by other studies, this research applies a linear programming method to optimize the agricultural activity in irrigated and rainfed areas. A case study was demonstrated in five farms and three Western Bahia counties, simulating rainfall delay and reduction conditions. Results show that the linear programming model can provide information to optimize the agricultural activity by recommending crops, seeding dates and cycle intervals, predicting harvest losses, and optimizing resource allocation. It is evident that in irrigated areas, the variation of rainfall scenarios has less impact on agricultural activity, enabling double-cropping and even continuous-cropping system. Applying the model at different water governance levels shows that it has good applicability as a tool for agriculture water management and to guide governance actions.

Keywords: Water governance. Rainfall delay. Irrigated agriculture.

1.2. INTRODUCTION

The rational use of water resources is a growing global concern. A water crisis is pointed to as one of the main global risks for next years in society. Despite interconnection with others, their effects are strongly linked to food and economic crises due to the potential reduction of crop yields caused by climate changes and water use conflicts of interest (WEF, 2020). The increase in the global population and the consequent demand for food coupled with agriculture's primary attribution to the global water withdrawal also support this concern (WWAP, 2016). The water crisis also reflects a governance crisis. The relationship between society, users, institutions, and the government is the key to provide rational management of water resources (CALVO-

MENDIETA; PETIT; VIVIEN, 2017; UNESCO, 2006). When applied in agricultural water management, this relationship has the general objective of optimizing the water use, reflecting the objectives of all stakeholders.

In Brazil, the MATOPIBA region (the acronym stands for the first two letters of Brazilian states of Maranhão, Piauí, Tocantins, and Bahia) is the last agricultural frontier in the country. It is characterized by rapid changes in land cover and land use. The agricultural expansion happened predominantly over natural vegetation areas in the Cerrado biome through a significant agricultural intensification (DIAS *et al.*, 2016). Within this region, the Western Bahia mesoregion stands out by its remarkable agricultural water management.

Western Bahia has an impressive performance in the regional economy. The 2.4 million hectares destined for agricultural production concentrates 34.2% of the state's agricultural GDP (gross domestic product) (AIBA, 2019b). Despite covering only 5.81% of the entire cropland, the irrigated area is responsible for 30% of the region's agricultural production value (AIBA, 2019a). This is possible by adopting a continuous agricultural production model and by increasing crop yields in these areas. In rainfed areas, this production model is not possible, and even double-cropping systems are threatened, mainly due to the marked water deficit of the dry season (ABRAHÃO; COSTA, 2018).

Agricultural in Western Bahia also has environmental impacts, mainly related the soil's physical properties and carbon sequestration. In the irrigated areas, the biomass production is less affected by water limitation, having a higher net primary production, but may also affect soil and water conservation (CAMPOS; PIRES; COSTA, 2020; DIONIZIO; COSTA, 2019).

Highly intensified in recent years, agricultural water use was identified as the main cause of water stress and conflicts. These conflicts could be mitigated by adopting a hydroclimatic monitoring system that would predict water availability in the months of greatest scarcity, guiding governance actions (POUSA *et al.*, 2019). Mantovani *et al.* (2019) also suggested that hydroclimatic monitoring should contain information about the surface and groundwater availability, land use, hydrological features, policy, and governance issues. A prototype of this system and all research data are available on the OBahia – Territorial and Water Intelligence Platform for Western Bahia (PIMENTA *et al.*, 2020). Additional information available on the platform is the forecast of the rainy season onset evaluated by Commar (2020). This prediction has the potential to strongly impact the regional agricultural economy, making it possible to optimize crop production in both irrigated and rainfed areas. Still, for this to be possible, it is necessary to develop optimization methodologies compatible with this hydroclimatic forecasting.

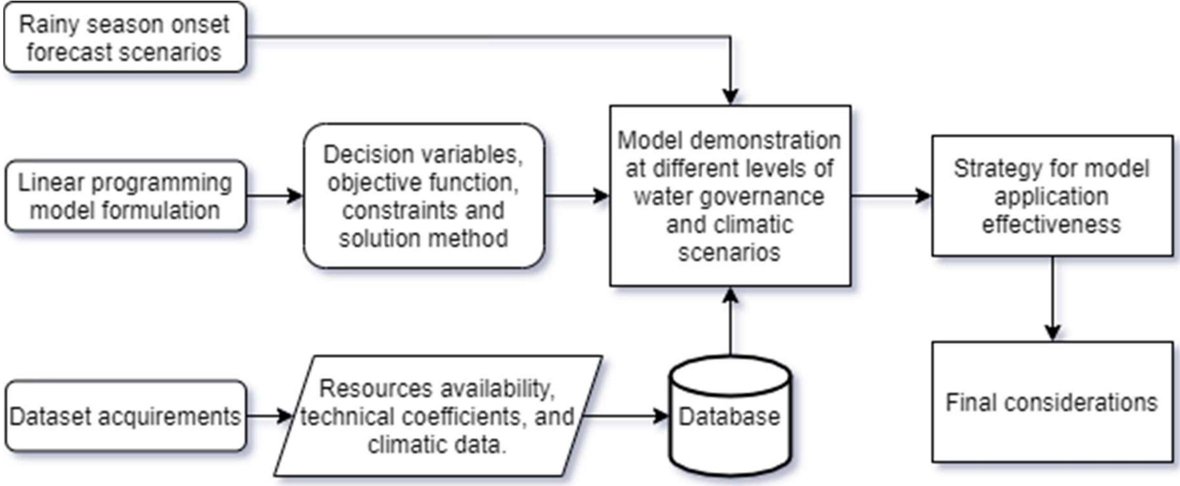
Several studies have been developed to optimize agricultural water use, especially related to irrigated areas. Linear programming has great usability in these studies with the problem formulation adapted to different objectives as: (1) optimize water allocation resources at different scales (ALJANABI; MAYS; FOX, 2018; CHEN *et al.*, 2019; FREIRE-GONZÁLEZ; DECKER; HALL, 2018; FU, JISI *et al.*, 2018; FU, QIANG *et al.*, 2018; JIN *et al.*, 2018; VEINTIMILLA-REYES *et al.*, 2019), with multiple objectives (LI *et al.*, 2020; SUO; WU; ZHOU, 2017), under parameter uncertainty (CHEN *et al.*, 2019; LI *et al.*, 2018, 2020), with small data series (ZHANG, CHENGLONG; GUO, 2018) and fuzzy variables and several other conditions (ZHANG, FAN *et al.*, 2018); (2) Maximize net economic benefits and minimize irrigation cost (MA *et al.*, 2019; SHEIBANI; SHOURIAN, 2019; SHIRSHAHI *et al.*, 2020); (3) Improve the irrigation management by reduction of water consumption (DIFALLAH *et al.*, 2017), maximization of irrigation efficiency (BEKCHANOV *et al.*, 2016) and agricultural water productivity (ZHAO *et al.*, 2017) using crop water production functions (JIANG *et al.*, 2018); (4) Improve and guide water governance actions (FU, QIANG *et al.*, 2018; ZHANG, FAN *et al.*, 2020); and (5) several other situations with multiple objectives, multi-scale, different data conditions, and evaluations (JIN *et al.*, 2018; LI *et al.*, 2020; NIU *et al.*, 2019; SUO; WU; ZHOU, 2017; TANG *et al.*, 2019; ZHANG, FAN *et al.*, 2019). In summary, linear programming is commonly used in agricultural water management, with a direct relationship between model robustness and data reliability and availability. Unfortunately, this robustness can sometimes make the model application unavailable for all governance levels, mainly because it requires a complex solution method.

This study proposes a linear programming model to operational optimization in in Western Bahia. The model optimizes agricultural output considering the rainy season onset forecast. Specifically, it is done by presenting the linear programming model formulation and solution, its application at different levels of water use, and the model potentials and limitations. Actions and strategies that illustrate the effectiveness of the model uses and the optimization of water use in agriculture are also indicated. Despite the relative simplicity of the model, it can be applied under real conditions by farmers and other decision-makers to manage water resources.

1.3. MATERIALS AND METHODS

This section, summarized in Figure 1, explains the process of acquiring, processing, and analyzing data, resulting in an economic assessment of the impacts of hydroclimatic forecasting in Western Bahia. The following topics are emphasized: (1) the linear programming model formulation, (2) dataset acquisition, and (3) the model application and analysis.

Figure 1 - Work flowchart



1.3.1. Data acquisition and processing

In a general way, the data acquisition depends on the water governance level considered in the model's analysis. At the farm governance level, data related to area availability (irrigated and rainfed), water grant, climatic data, unit production cost, and other technical coefficients (unit need for machinery and manual labor) and adopted crops were obtained from interviews and local consultation. Otherwise, at the municipal governance level, area availability and water grant were obtained from OBahia (PIMENTA *et al.*, 2020), climate data were obtained from "*Banco de Dados Meteorológicos do INMET*" (INMET, 2020), selecting at least 30 years of daily data for each weather station available, unit production cost were obtained from "*Série Histórica de Dados*" (CONAB, 2020b). In both cases, each crop's unit revenue value was obtained from "*Preços agrícolas, da sociobio e da pesca*" (CONAB, 2020a). Geographic information was processed using QGIS 3.10 (2020), while temporal and climatic data were processed using Microsoft Excel® and Python 3.8 (VAN ROSSUM; DRAKE JR, 1995).

The weather data were fit to a normal distribution where the average and quartiles (25 and 75%) were obtained to represent each municipality's climatic condition. In irrigated conditions, total water availability is represented by the sum of rainfall and water grant available.

The resource availability and needs were finally converted to represent the fortnightly period, making the model application compatible with the hydroclimatic forecast available for the region (COMMAR, 2020; PIMENTA *et al.*, 2020).

1.3.2. Model formulation

A linear programming model (LPM) formulation is fully described by Vanderbei (2014) and Luenberger and Ye (2016). This section highlights the definition of decision variables, the objective function, constraints, and solution method.

1.3.2.1. Decision variables

The decision variables (DV) in this study were defined as the planted area of a crop, under irrigated or rainfed condition, with a specific crop cycle, planted in a specific fortnight. Mathematically, DV can be demonstrated as X_{ijkl}, where "X" (hectares) is the optimum value for planted area, "i" is the crop type, which may be soybeans, maize, beans or cotton, "j" is the planting system, which may be irrigated or rainfed, "k" is the crop cycle type, which may be short, average, or long and "l" is the evaluated period defined by agroclimatic zoning made by CONAB (2019).

1.3.2.1. Objective Function

The objective function (OF) of this optimization model is to maximize the net benefit (NB) (R$ ha^{-1}) of agricultural activity, been mathematically expressed as:

$$\text{Maximize NB} = \sum \text{Rijkl} \times \text{Xijlk} - \sum \text{Cijkl} \times \text{Xijlk} \tag{1}$$

where C (R$ ha^{-1}) is the unitary production cost value and R (R$ ha^{-1}) is the unitary revenue value.

1.3.2.2. Constraints and solution method

The constraints are based on agricultural use of resources (Res) been divided into land, work, machines, and capital. Land constraints refer to area (irrigated or rainfed) occupation; work constraints refer to labor and administrative activities; machines constraints refer to agricultural machinery's availability as planter or harvester; capital constraints mean the working capital of activity. In all cases, the resource demand was computed but used as constraints just when that information is substantial for the management level considered, defined in the case study section. In all constraint's conditions, the use of the resources must be equal or less than their availability (Equation 2):

$$\text{Res. Demand} \leq \text{Res. Availability} \tag{2}$$

In a general way, the resource demand is described by Equation 3, being the product between the optimum DV and the resource unitary amount needs.

$$\text{Res. Demand} = \sum \text{Xijkl} \times \bar{\text{Y}}\text{ijlk} \tag{3}$$

where $\bar{Y}$ (dimensionless) is the adopted technical coefficient for each resource, representing the unitary amount needs.

Crop water demand (CWD) was the only constraint parameter calculated differently than described by Equation 3. CWD is calculated by several steps. First, the reference evapotranspiration ETo (mm day^{-1}) and the crop evapotranspiration ETc (mm day^{-1}) accumulated for the period were calculated. ETc is the product between ETo and the crop coefficient Kc (dimensionless), according to Allen *et al.* (1998) (Equation 4):

$$\mathrm{ETc} = \mathrm{ETo} \times Kc_{ijkl} \tag{4}$$

Santos *et al.* (2020) evaluated the impact of controlled water deficit on crop yields in Cerrado's condition, shown that for a 20% reduction in ETc for cotton and soybean, 12% for maize, 13% for bean and 15% for wheat there is no significant reduction in crop yields. Based on this work CWD was defined as the product between the related ETc and a potential crop evapotranspiration reduction that does not cause a significant yield reduction (Kr, adimensional). In turn, adopted Kr for each crop was 0.80 for cotton and soybean, 0.88 for maize, 0.87 for bean and 0.85 for wheat.

Therefore, CWD for each DV is mathematically described by Equation 5:

$$CWD_{Xijkl} = \sum X_{ijkl} \times ETc \times Kr_{ijkl} \tag{5}$$

The Solver tool, which is part of Microsoft Excel, was used for the model solution.

1.3.3. Model application and analysis

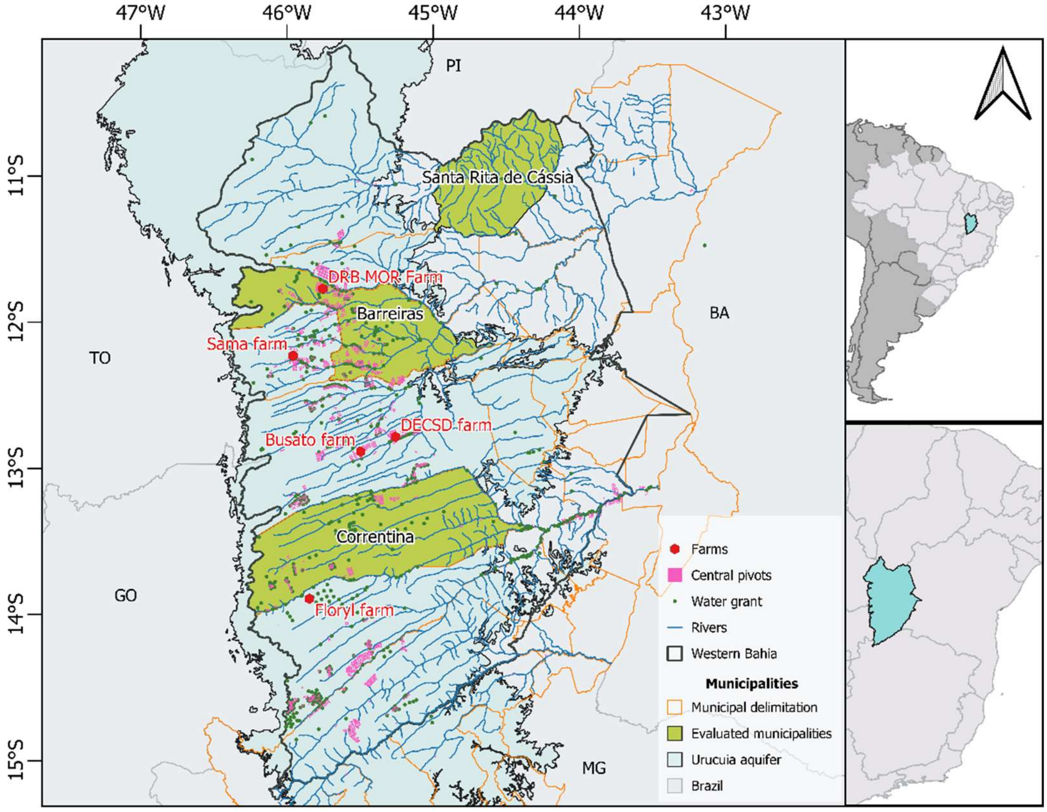
The model application was considered at two levels of water governance, at the farm and municipal levels. Farm level is the main decision maker related to the withdrawal of water for agricultural use, while the municipal level was considered to have a direct relationship with the farms in terms of income generation and tax collection of areas agricultural.

At the farm level, the model was applied considering the original climatic condition and in five scenarios of rainfall delay (D0, D1, D2, D3, and D4, representing 0, 1, 2, 3, and 4 fortnights in the onset of the rainy season, respectively) and rainfall reduction (R0, R5, R10, R15, R20 representing 0%, 5%, 10%, 15%, and 20% of rainfall reduction, respectively). At the municipal level, the original climatic conditions were represented by the average values. In addition to analyzing possible rainfall delays and reductions, the model was also applied for quartile conditions. Original analysis has the same climatic conditions as R0 and D0, being omitted from the graphs. When available, the actual area occupation was compared with the results of the model application. All characteristics of the LPM application are fully described in the case studies section.

1.4. CASE STUDIES

The study area (Figure 2) is in the western part of Bahia's state (43.23° to 46.61°W, 10.10° to 15.26°S), bordering the Brazilian states of Minas Gerais, Goiás, Tocantins e Piauí. According to the AIBA (2021) (Bahia Farmers and Irrigators Association), Western Bahia can be described in two predominant regions, the valley, with traditionally small-scale and subsistence agriculture, and the "Cerrado," a region of business agriculture. The region's representative climate is tropical with a dry season, characteristics that, when combined with the flat topography, favored the development of irrigated agriculture using the center pivot system. Due to data availability, the model application was made at five farms and three municipalities that are representative of the region's agriculture.

Figure 2 - General view of Western Bahia, representing the municipalities and farms used in the case studies. Red dots represent the farms' location. Green dots are the water grant points. The Urucuia aquifer and the rivers are the source of water for irrigation. Pink areas represent the irrigated area by center pivots.



1.4.1. Farm and municipal characterization

Five farms served as case studies at the farm governance level: (1) Sama, where the model was applied to optimize the Soybean crop season with different cycle duration and planting dates in rainfed and irrigated areas; (2) Floryl, for multiple crops with multiple cycle duration, (3) DRB MOR ("*Decisão Rio Branco e Morena Farm*") and (4) DECSD ("*Decisão São Desidério Farm*") for multiple crops during six seasons and finally (5) Busato, for multiple crops in a season. These farms were selected mainly for having a management model that made data available for this study. The resources availability, crops, and season are summarized in Table 1.

Table 1 - Farm, resource availability, crops, and season.

Farm	Resource availability			Evaluated Crop	Season
	Area (hectares)		Water grant (m^3 day^{-1})		
	Irrigated	Rainfed			
Sama	1,221.10	878.5	39,297.5	Rainfed soybean[1]; Irrigated soybean[2]	2018/19
Floryl	950.00	120.00	68,437.00	Maize 1° crop3; Maize 2° crop3; Soybean3	2019/20
DRB MOR	4,267.00	646.00	101,760.00	Cotton; Bean 1° crop; Bean 2° crop; Maize 1° crop; Maize 2° crop; Soybean; Wheat	2017[AW]; 2017[SS]; 2018[AW], 2018[SS], 2019[AW], 2019[SS]
DECSD	3,299.00	0.00	156,552.00		
Busato	4,246.80	676.00	23,240.00	Cotton; Maize 1° crop; Maize 2° crop; Soybean	2019/2020

[1] Average and long cycle

[2] Short, average and long cycle

[AW] Autum/winter

[SS] Spring/summer

Three municipalities served as case studies at the municipal governance level: (1) Barreiras, with the largest irrigated area, (2) Correntina, a region with the largest rainfed agricultural area, and (3) Santa Rita de Cássia, a region with low technology agriculture. In all cases, cotton, beans, soybeans, and maize were evaluated during six crop seasons. For the municipal water governance level, the resources availability, crops, and season are summarized in Table 2.

Table 2 - County, resource availability, crops, and season.

County	Resource availability			Evaluated Crop	Season
	Area (hectares)[1]		Water grant (m^3 day^{-1})		
	Irrigated	Rainfed			
Barreiras	42,760.00	291,948.00	4,586,256.52	Cotton; bean; Maize and soybean.	2018[SS]; 2019[AW]; 2019[SS]; 2020[AW]; 2020[SS] and 2021[AW]
Correntina	15,008.00	408,022.00	2,444,307.23		
Santa Rita de Cássia	60.00	7,293.00	44,000.00		

[AW] Autum/winter

[SS] Spring/summer

Sama farm presented ETo values between 45.24 and 96.94 mm and rainfall between 0.00 and 172.80 mm, in each time step (fortnight) (Figure 3). Floryl farm, in turn, presented lower values of ETo, between 42.70 and 86.69 mm, and rainfall, between 0.00 and 142.80 mm (Figure 4). The DRBMOR Farm (Figure 5) presented ETo between 46.20 and 107.53 mm, and rainfall between 0.00 and 142.8 mm. At DECSD farm (Figure 6), the ETo values were between 43.13 and 89.85 mm, and rainfall between 0.00 and 232.20 mm. Finally, at Busato farm (Figure 7), ETo was between 41.12 and 94.74 mm and rainfall between 0.00 and 168.80 mm. If climate data was not available, it was considered equal to the previous year's correspondent period.

Figure 3 - ETo and rainfall at Sama farm.

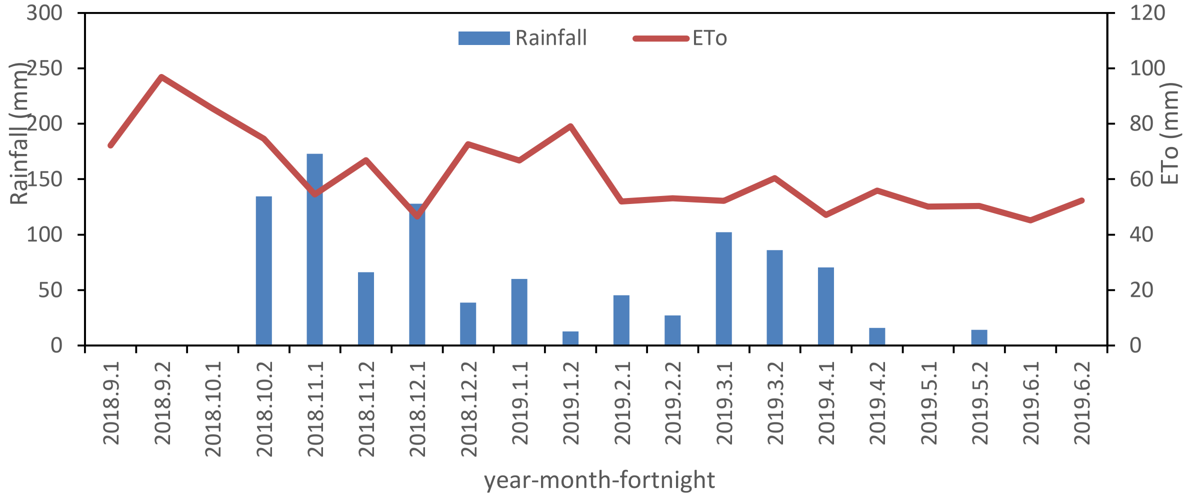


Figure 4 - ETo and rainfall at Floryl farm.

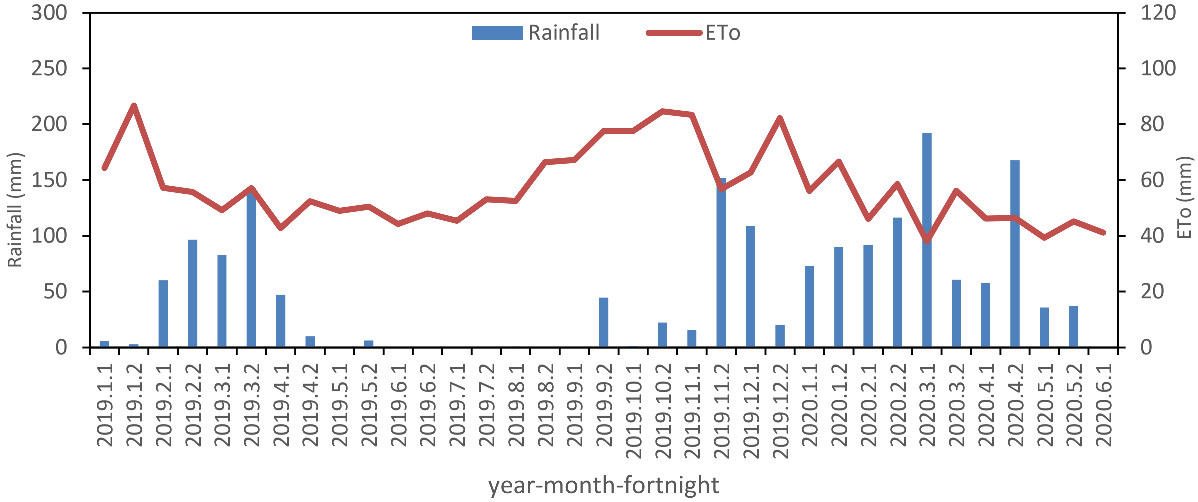


Figure 5 - ETo and rainfall at DRBMOR farm.

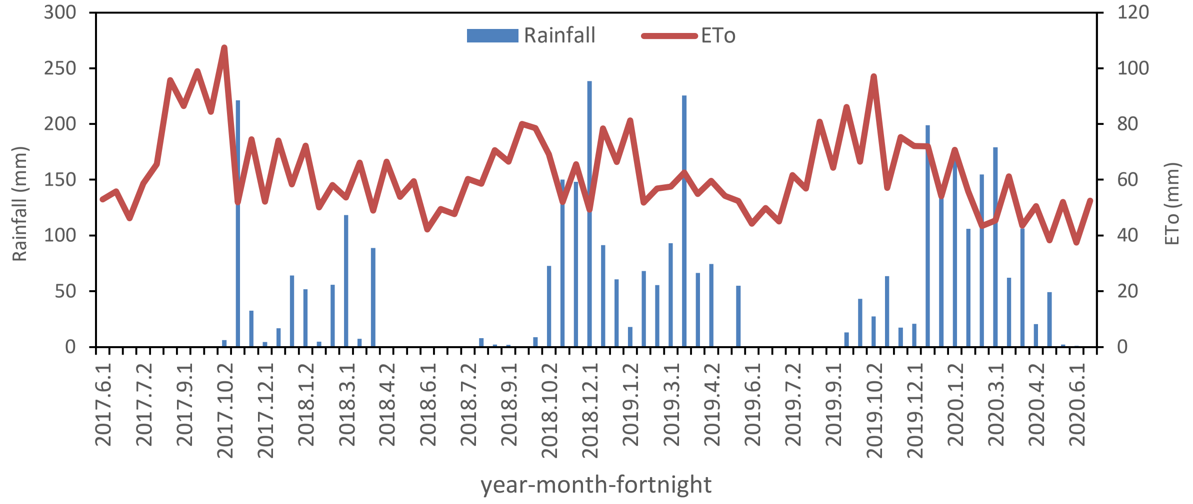


Figure 6 - ETo and rainfall at DECSD farm.

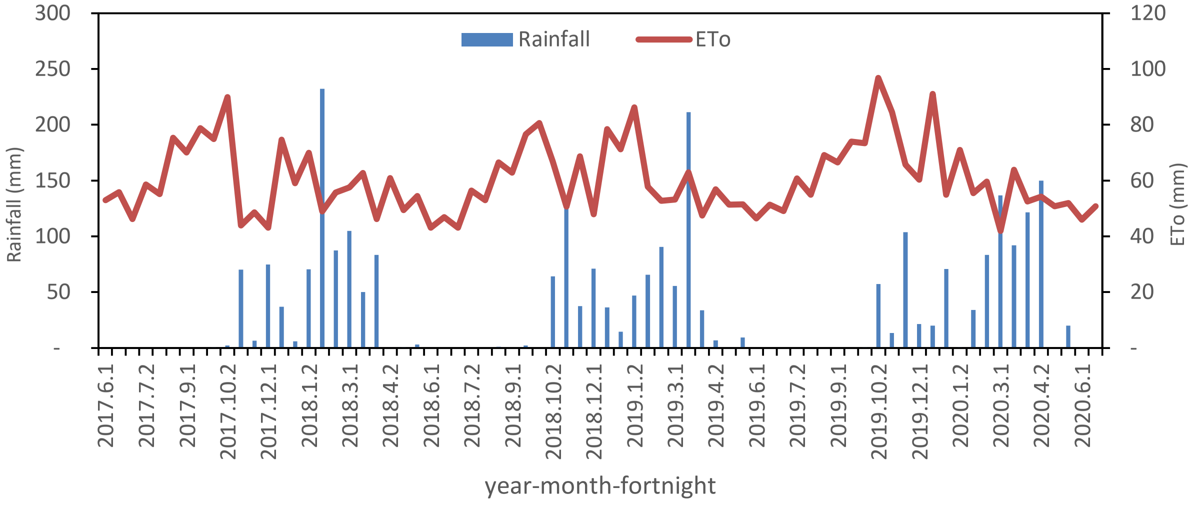
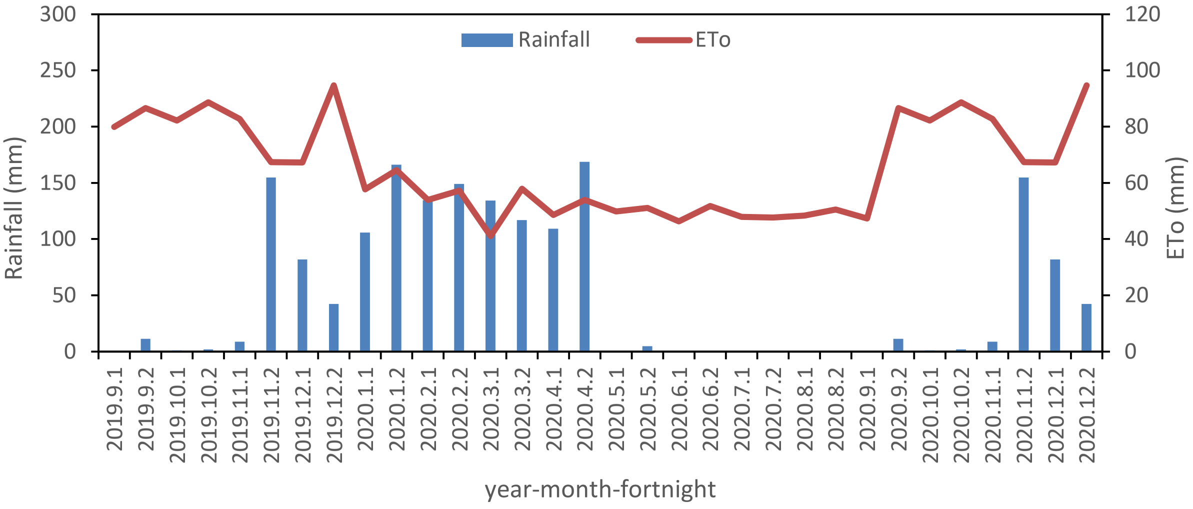


Figure 7 - ETo and rainfall at Busato farm.



Barreiras (Figure 8), Correntina (Figure 9), and Santa Rita de Cássia (Figure 10) presented ETo values between 54.72 and 88.62, 54.49 and 84.76, 58.95 and 91.64 mm, respectively. In turn, rainfall presented values between 0.22 and 103.69, 0.22 and 108.72, 0.01 and 101.49 mm, respectively. The figures show the rainfall mean and interquartile range of data distribution.

Figure 8 - ETo and rainfall (mean values) at Barreiras, lines above bar represent the interquartile range.

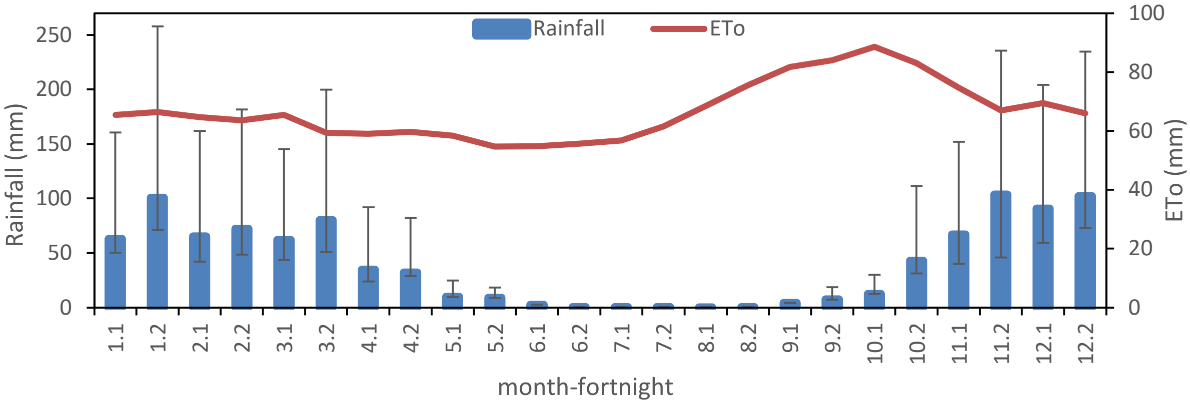


Figure 9 – ETo and rainfall (mean values) at Correntina, lines above bar represent the interquartile range.

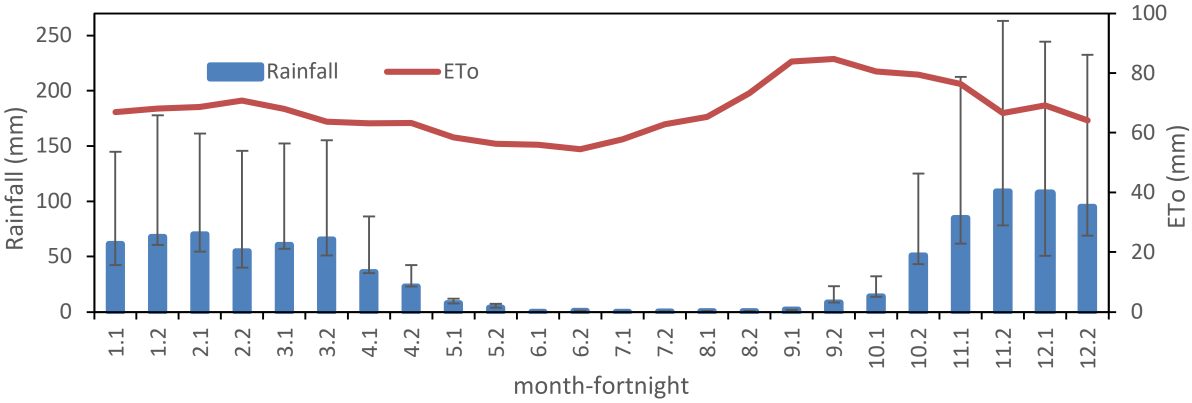
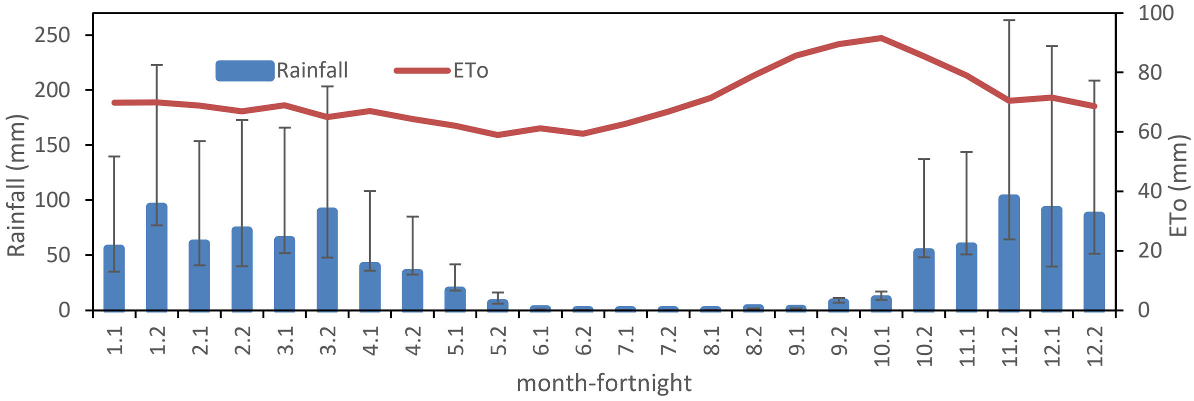


Figure 10 – ETo and rainfall (mean values) at Santa Rita de Cássia, lines above bar represent the interquartile range.



1.4.2. Crop characterization

Crop options for each evaluated LPM have already been presented in Tables 1 and 2. Table 3 shows the adopted characteristics for each crop. These data are representative of the Western Bahia region and are usually adopted by companies that provide irrigation consulting services, as Irriger Connect® (name adopted in Brazil for the company Valley Scheduling®).

Table 3 – Crop, cycle and duration, Kc (initial, average, and final), Kr, and range seeding time.

Crop	Cycle	Duration (fortnight)	Kc initial	Kc average	Kc final	Kr	Range seeding time (fortnight-month)
Soybeans	short	8	0.60	1.00	0.70	0.80	1-10 to 2-02
Soybeans	average	9	0.60	1.00	0.70	0.80	1-10 to 2-02
Soybeans	long	10	0.60	1.00	0.70	0.80	1-10 to 2-02
Maize 1° season	average	9	0.65	1.00	0.60	0.88	1-10 to 2-02
Maize 2° season	average	9	0.65	1.00	0.60	0.88	1-05 to 2-06
Maize 1° season	long	12	0.60	1.00	0.50	0.88	1-10 to 2-02
Maize 2° season	long	12	0.60	1.00	0.50	0.88	1-05 to 2-06
Cotton	long	14	0.50	0.90	0.38	0.80	1-11 to 2-02
Bean 1° season	average	7	0.70	1.20	0.60	0.87	1-10 to 2-02
Bean 2° season	average	7	0.70	1.20	0.60	0.87	1-04 to 2-06
Wheat	average	8	0.70	1.20	0.40	0.85	1-08 to 2-09

1.4.3. LPM constraints setup

For each application and LPM analysis, a different restriction's setup was adopted. These restrictions may be the irrigated (Ia) or rainfed area (Ra), CWD irrigated (CwdI) or rainfed areas (DwdR), labor (L), or machinery (M). This setup difference was necessary due to the solution tool's limitations and can be fully checked in Table 4.

Table 4 – Constraint setup for each LPM application and analysis.

Analysis	Farms					Counties		
	Sama	Floryl	DRB MOR	DECSD	Busato	Barreiras	Correntina	Sta. R. C.
Original	Ia, Ra, CwdI	-	-	-	-	Ia, Ra, DwdI, CwdR	Ia, Ra, DwdI, CwdR	Ia, Ra, DwdI, CwdR
Irrigated original	Ia, CwdI, L, M	Ia, CwdI	Ia, CwdI	Ia, CwdI	Ia, CwdI	Ia, Ra, DwdI, CwdR	Ia, Ra, DwdI, CwdR	Ia, Ra, DwdI, CwdR
Irrigated rain delay								
Irrigated rain reduction								
Rainfed original	Ra, CwdR, L, M	Ra, CwdR	Ra, CwdR	-	Ra, CwdR	Ia, Ra, DwdI, CwdR	Ia, Ra, DwdI, CwdR	Ia, Ra, DwdI, CwdR
Rainfed rain delay								
Rainfed rain reduction								

Ia	Irrigated area availability
Ra	Rainfed area availabilty
Cwd	Crop Water Demand
CwdI	Crop water demand in irrigated area
CwdR	Crop water demand in rainfed area
L	Labor
M	Machinery

1.5. RESULTS

This section presents the results of applying the LPM for the Western Bahia farms and counties, followed by its potentials, limitations, and a strategy for making the LPM an effective tool for water governance in the region. Sama, DRBMOR, DECSD, and Busato farms are included in the regions of intense irrigation systems growth presented by Pousa *et al.* (2019).

1.5.1. LPM results

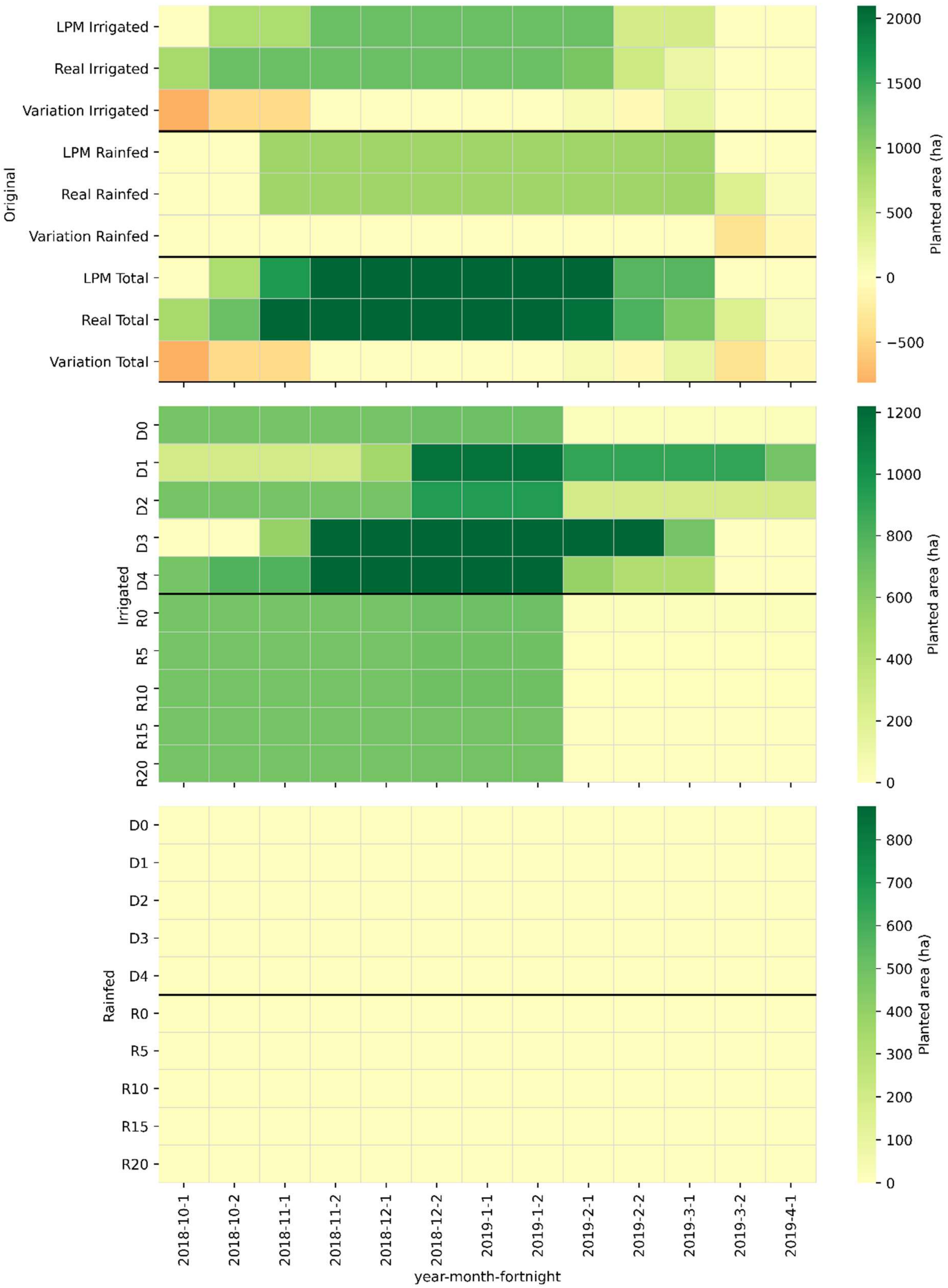
1.5.1.1. Sama farm

At Sama farm, the result of applying the LPM differs from real decisions made by farmers. In irrigated areas, the LPM's seeding recommendation was later compared to the real conditions, while the harvest indication was like the real condition. In rainfed areas, without considering crop water demand as a constraint, only a small difference in the harvest date is noticeable in comparing the LPM and actual condition due to changes in the crop's cycle.

In irrigated areas, in rainfall delay conditions, the LPM's responses considered the best price for crops commercialization and best distribution of labor and machinery distribution. For these areas, in rainfall reduction scenarios, the LPM's responses do not differ between them because irrigation can supply the crop water deficit during cultivation.

In rainfed areas, when considering the crop water demand, the LPM's response was not to plant, and without this restriction, the response was like the real decision, differing only in the harvest period. This recommendation of not plant in rainfed areas is because the crop's water deficit, in simulated conditions, is higher than the one proposed by Santos *et al.* (2020), which can cause productivity losses. In actual conditions, the difference between expected and actual productivity in rainfed areas had average values of 12% and up to 61%. All LPM's responses are demonstrated in Figure 11.

Figure 11 – Planted area, in hectares, recommended by LPM for original and irrigated conditions of Sama farm.

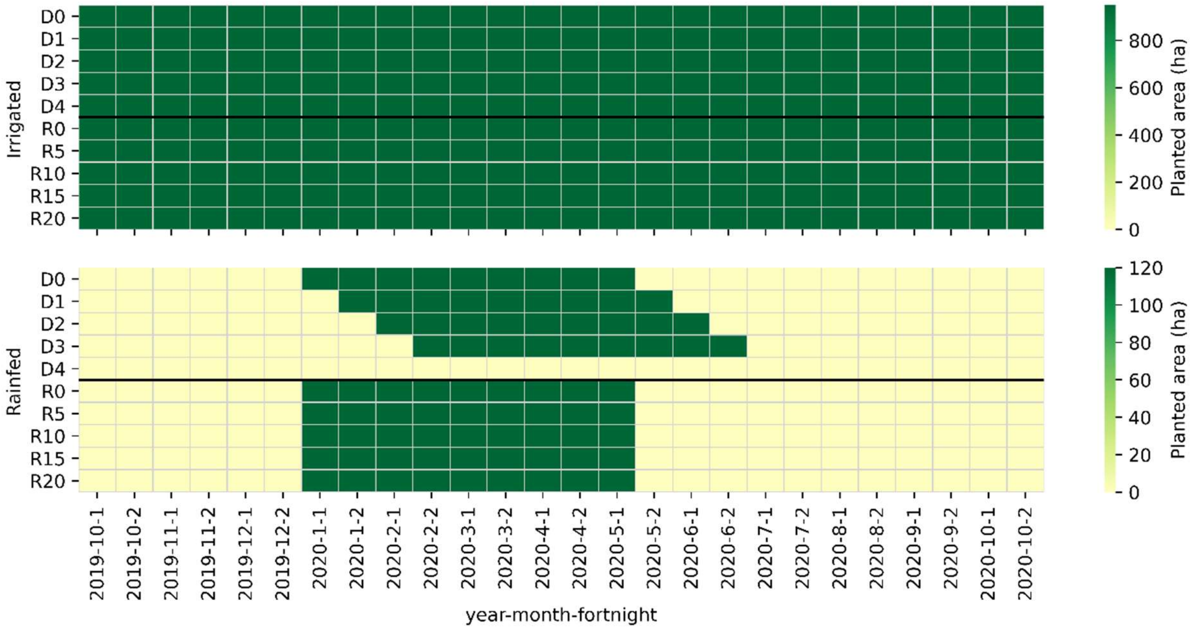


1.5.1.2. Floryl farm

At Floryl farm, the LPM optimizes (in all conditions of rainfall delay or reduction) the area occupied in irrigated areas recommending the seeding of soybeans (from October to February) followed by maize 1st crop (from February to June) and then by maize 2nd crop (from June to October). Double-cropping systems are common in Brazil, where almost 58% of maize is produced in these conditions (ABRAHÃO; COSTA, 2018), but the adoption of continuous monoculture (maize 1st and 2nd crop) may not be recommended due to the increase of pathogen's population in the area, which can reduce the productivity of the second crop (BULLOCK, 1992).

In rainfed areas, the LPM's response was to plant maize 1st crop on all occasions, adjusting the seeding date in rainfall delay conditions. In the condition of delay of four fortnights in the rain, the maize 1st crop's seeding was not recommended because it is out of the CONAB recommended planting schedule (2019). This result is also consistent with the assessment made by Abrahão and Costa (2018), where the rainfall delay is one of the threats to double-cropping systems. All LPM results of area occupation can be verified in Figure 12.

Figure 12 - Planted area, in hectares, recommended by LPM for irrigated and rainfed conditions of Floryl farm.



1.5.1.3. DRBMOR and DECSD farms

The results for the DRBMOR farm were like the Floryl farm. In irrigated areas, the LPM's responses favor higher area occupation by seeding cotton and bean 2nd crop between November 2017 and September 2018, followed by seeding bean 1st crop, cotton, and wheat between November 2018 and January 2020, in all scenarios of rainfall delay or reduction.

At rainfed areas, the recommendation was to plant cotton after September 2019 and December 2020, adjusting the planting dates according to rain delay conditions. It is perceptible that in the period from 2017 to 2019, it was not recommended crops in rainfed areas due to the accentuated water deficit, which evidences that in drier years, the productivity of irrigated area is higher than rainfed.

At DECSD farm, rainfed areas are not cultivated, and the LPM responses are the same as that DRBMOR farm. LPM results for the DRBMOR farm are shown in Figure 13, while for DECSD are in Figure 14.

Figure 13 - Planted area, in hectares, recommended by LPM for irrigated and rainfed conditions at the DRBMOR farm.

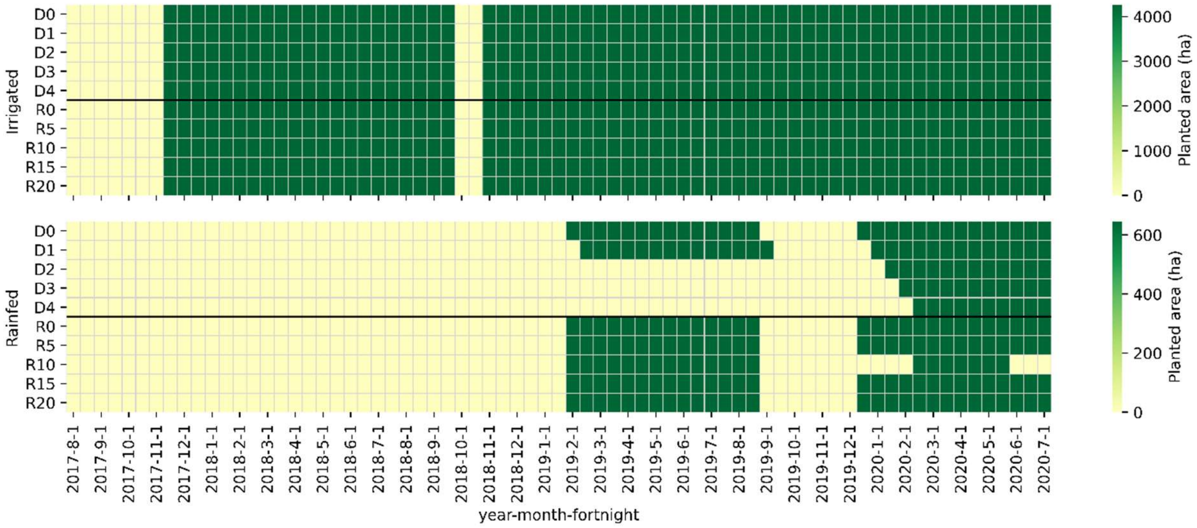
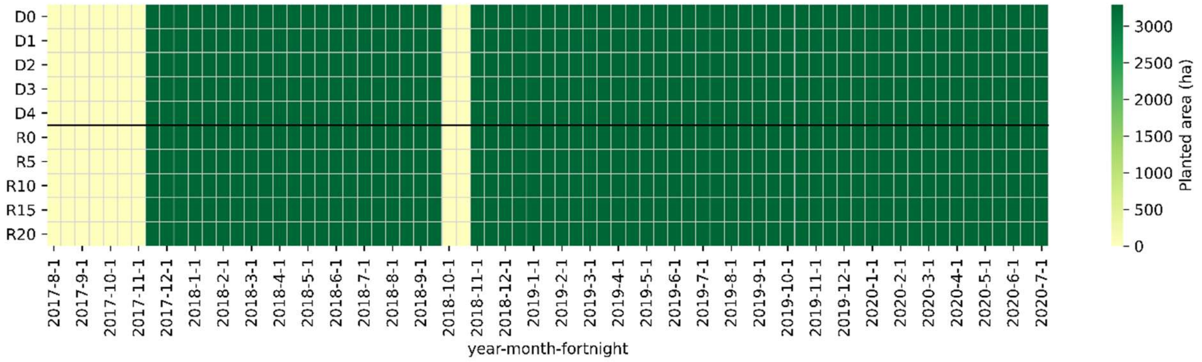


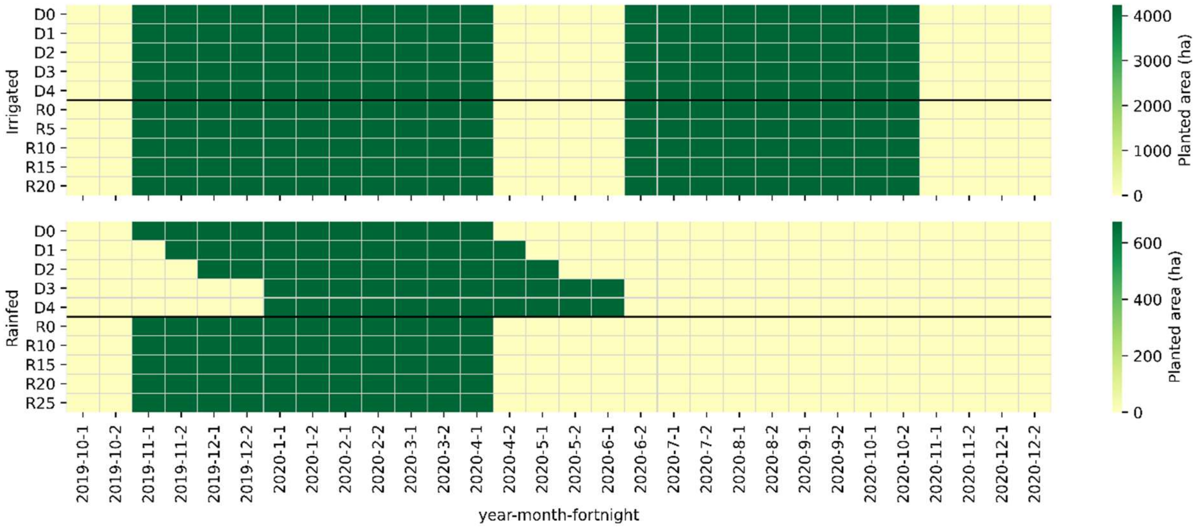
Figure 14 - Planted area, in hectares, recommended by LPM for irrigated conditions at the DECSD farm.



1.5.1.4. Busato farm

At the Busato farm, in irrigated areas, the LPM's recommendation is a double-cropping system composed of cotton and maize 2nd crop for all occasions of rainfall delay or reduction. In rainfed areas, just cotton was recommended, adjusting the seeding date in rainfall delay scenarios. Again, the double-cropping system is threatened by accentuated water deficit, as pointed by Abrahão and Costa (2018). All results are shown in Figure 15.

Figure 15 - Planted area, in hectares, recommended by LPM for irrigated and rainfed conditions at the Busato farm.



1.5.1.5. Barreiras, Correntina and Santa Rita de Cássia

For municipal water governance, the LPM was applied in rainfall average (original), delay, reduction, and in 1st (Q25) and 3rd (Q75) quartile of data distribution.

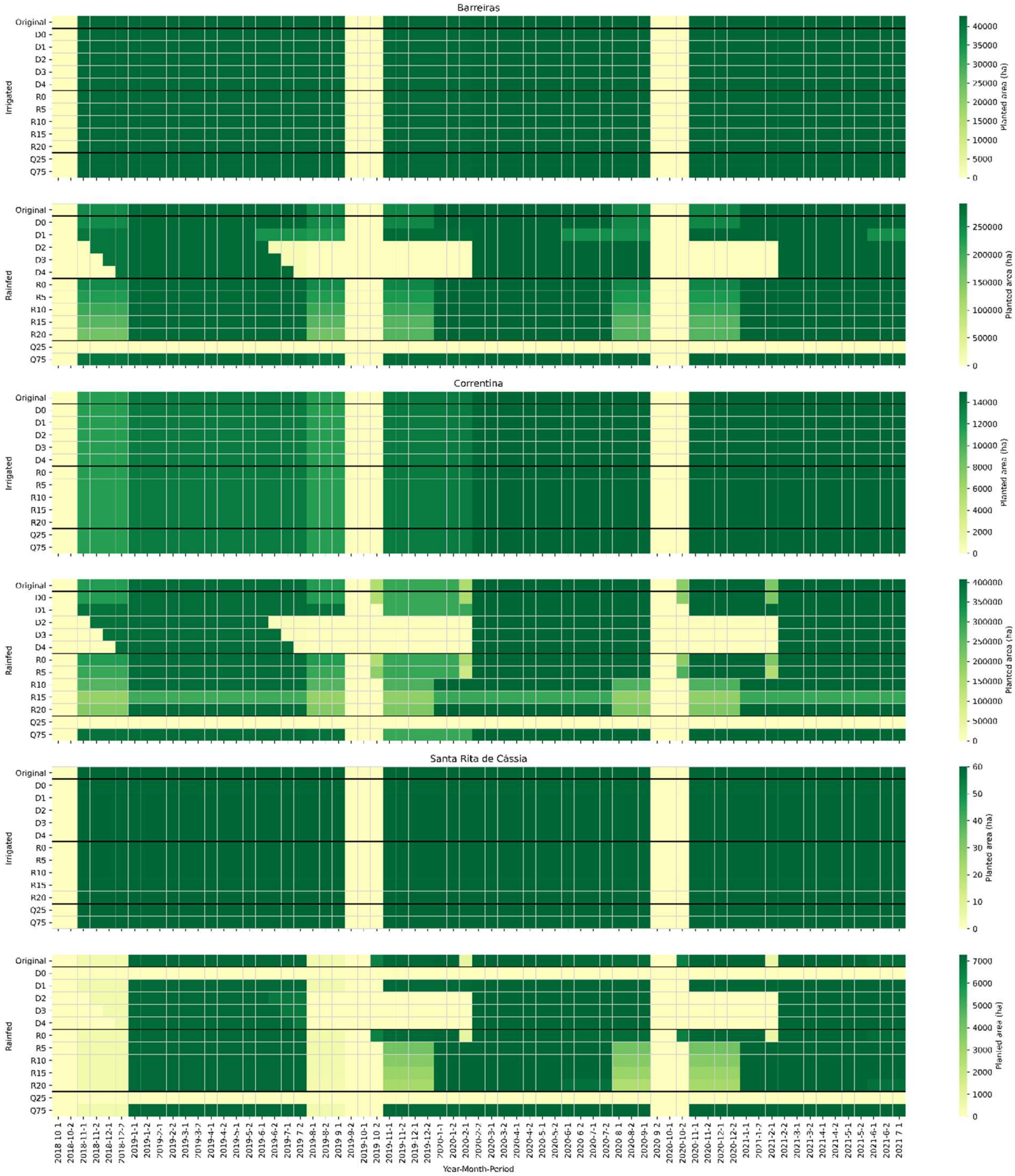
Results for Barreiras shows a good optimization of area occupation. The predominant recommendation is the double-cropping system with bean 1st crop and cotton in irrigated and rainfed areas. Irrigated areas maintain the same results for all evaluated conditions. Under some rainfall delay conditions, rainfed lands cannot be capable of a double-cropping system and present a greater vacancy than the irrigated lands. In extremely dry years scenarios (Q25), the LPM recommendation is not to plant in rainfed areas, indicating a possibility of a decline in crop productivity.

Correntina and Santa Rita de Cássia results resembled the Barreiras results, with cotton and beans in a double-cropping system for irrigated areas. The model indicated an accentuated water deficit in some conditions in rainfed areas that may cause a reduction of productivity, threatening the double-cropping systems.

Among those evaluated, Barreiras is the municipality with the highest proportion of irrigated area to total cropland (12.78%). On the other hand, Correntina and Santa Rita de Cássia have smaller proportions (3.54% and 0.81%, respectively). Despite not being in regions of intense irrigation growth, Correntina has been the scene of conflicts over water resources (G1, 2017). Santa Rita de Cássia and other regions not evaluated in the study have a vast potential for the development of irrigated agriculture by center pivot systems. Still, suitability and technical limitations must be considered (as energy availability, topography, climatic conditions, and logistical aspects), and beyond these, also the environmental, economic, and social implications of possible development.

The complete results of the LPM application to Barreiras, Correntina, and Santa Rita de Cássia are shown in Figure 16.

Figure 16 - Planted area, in hectares, recommended by LPM for irrigated and rainfed conditions of Barreiras, Correntina, and Santa Rita de Cássia.



1.6. DISCUSSION

Presented results are consistent with those found by other studies. First, there was a success in applying the model at different levels of water use, as demonstrated by Aljanabi, Mays, and Fox (2018); Chen *et al.* (2019); Freire-González, Decker, and Hall (2018); Fu, Jisi *et al.* (2018); Fu, Qiang *et al.* (2018); Jin *et al.* (2018) and Veintimilla-Reyes *et al.* (2019). Second, the model application was successful in maximizing the economic benefit of agricultural activity, as demonstrated by Ma *et al.* (2019), Sheibani and Shourian (2019), and Shirshani *et al.* (2020).

The application of this linear programming model can provide accurate information to guide actions for water resources governance in western Bahia. The first information was related to the areas' productive potential, given delayed and reduced rainfall conditions. By adapting the water availability for each watershed, it is possible to estimate the potential of irrigated agricultural expansion over rainfed areas in Western Bahia as the maximum water withdrawal must be equal to or less than the grant availability.

Finally, other more complex models can also be integrated into this to generate better information for decision-makers. An example is a multi-objective optimization model, directing the optimization to maximize the economic output and minimize water resource consumption.

1.6.1. LPM potential

The linear programming model presented in this study has several characteristics that allow water resources management and governance in Western Bahia, Brazil. The first characteristic is that the LPM can assist the decision-making process at different water governance levels from the farmers to municipal and regional levels.

LPM can define crops in irrigated and rainfed areas, maximizing agricultural activity's net economic benefit. In this process, the model can also optimize the use of human, capital, and machinery resources available for agricultural activity. LPM can also predict a harvest loss due to water deficit and calculate the water withdrawal of natural sources and labor, machinery, and capital demand during the crop season.

As final, being relatively simple and requiring few input variables, the model can be easily understood and easily disseminated for different uses.

1.6.2. LPM limitations

The proposed linear programming model has several limitations. First, agricultural systems do not have a linear response for all variables, such as crop yield response to the water stress and variations in irrigation cost. Due to a non-linear relationship between some variables, LPM may be inaccurate in some cases.

Second, the presented LPM application does not consider the spatial variation of climatic parameters, representing a limitation for evaluation at higher water governance levels as a mesoregion.

The Microsoft Excel® Solver tool, used for the linear programming model's solution, has a serious limitation of 200 decision variables and 100 constraints for each evaluation, requiring splitting the evaluation period in some cases to make the model size compatible with the limitation.

1.6.3. Strategy for LPM effectiveness

For the effectiveness of linear programming model for water resources management and governance in Western Bahia, the following strategy is recommended: (1) Develop an online tool with the linear programming model, which can be made available on the OBahia platform (PIMENTA *et al.*, 2020) integrating water availability data and the beginning of rainy season presented by other studies, (2) Adjust the technical crop coefficients (need of resources, yield, and Kc for example) for regional conditions and make them available by default on the platform and (3) promote training for farmers and other decisions makers aiming at the dissemination and correct use of the online tool, demonstrating its potential for use and the possibilities of analysis. The development of other studies may also favor the accuracy of the linear programming model's responses, such as studying the behavior of the marketing prices of crops over the years and a rainfall forecast for the 7 to 12 months after the beginning of the rainy season.

1.7. CONCLUSIONS

Concerns about the water crisis and its environmental, social, and economic impacts on agriculture activity have been increasing in recent years, especially in regions with extensive development of irrigated agriculture, such as in Western Bahia. Thus, it is necessary to develop tools that enable governance and water resources management. This study presented a linear programming model that can be used for this objective.

The LPM maximizes the net profit of agricultural activity in irrigated and rainfed areas. This model application was demonstrated in different water use levels, simulating different conditions of rainfall delay and reduction. Results show that the model's response can provide a good orientation for decision making, especially in a region where the adoption of double or continuous cropping systems is usual.

For the model to be used efficiently in the next harvests, a strategy for making available and training the methodology's use by farmers and other decision-makers is mentioned.

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2. ECONOMIC INDICATORS AND POSSIBLE GAINS WITH THE RAINY SEASON ONSET FORECAST IN WESTERN BAHIA.

2.1. ABSTRACT

Irrigated agriculture is seen as a key factor for Western Bahia's economy, with the potential to impact 30% of the value of agricultural production. This work aims to simulate the results of irrigated agriculture for the crop yield, water productivity, gross profit of agricultural activity, and water profitability, as well as to compare the possible gains by adopting information from the hydroclimatic forecasting model. Results show that one hectare of irrigated cropland is equivalent to 3.90 hectares of rainfed cropland on average. Adopting the forecast system for the beginning of the rains may increase the generation of revenue from agricultural areas by up to 30%.

Keywords: Water productivity. Agricultural production value. Water management.

2.2. INTRODUCTION

Irrigated agriculture is currently seen as a key factor for world agricultural development. In Brazil, irrigated agriculture's major impacts include higher productivity, reduction of the unit cost of production, and the possibility of a continuous-cropping system compared to rainfed areas (ANA, 2017).

The accelerated development of irrigated agriculture in Western Bahia has meant that this region currently has a substantial participation in the state economy. Despite representing only 5.81% of the state agricultural area, the regional agricultural production reaches 30% of the state agriculture output value (AIBA, 2019). As a region of great economic importance, and with the growing concern about water resources, several authors have directed studies that present data and tools that can optimize regional agricultural activity.

Pousa et al. (2019) suggested a hydroclimatic monitoring system to closely examine the water availability in months of water scarcity. A prototype of this system and all research data are available on the OBahia – Territorial and Water Intelligence Platform for Western Bahia (PIMENTA et al., 2020). The rainy season onset forecast tool is one of the components of the OBahia system. This forecast can provide farmers with a prediction of the best seeding date, relevant information in the agriculture decision-making process.

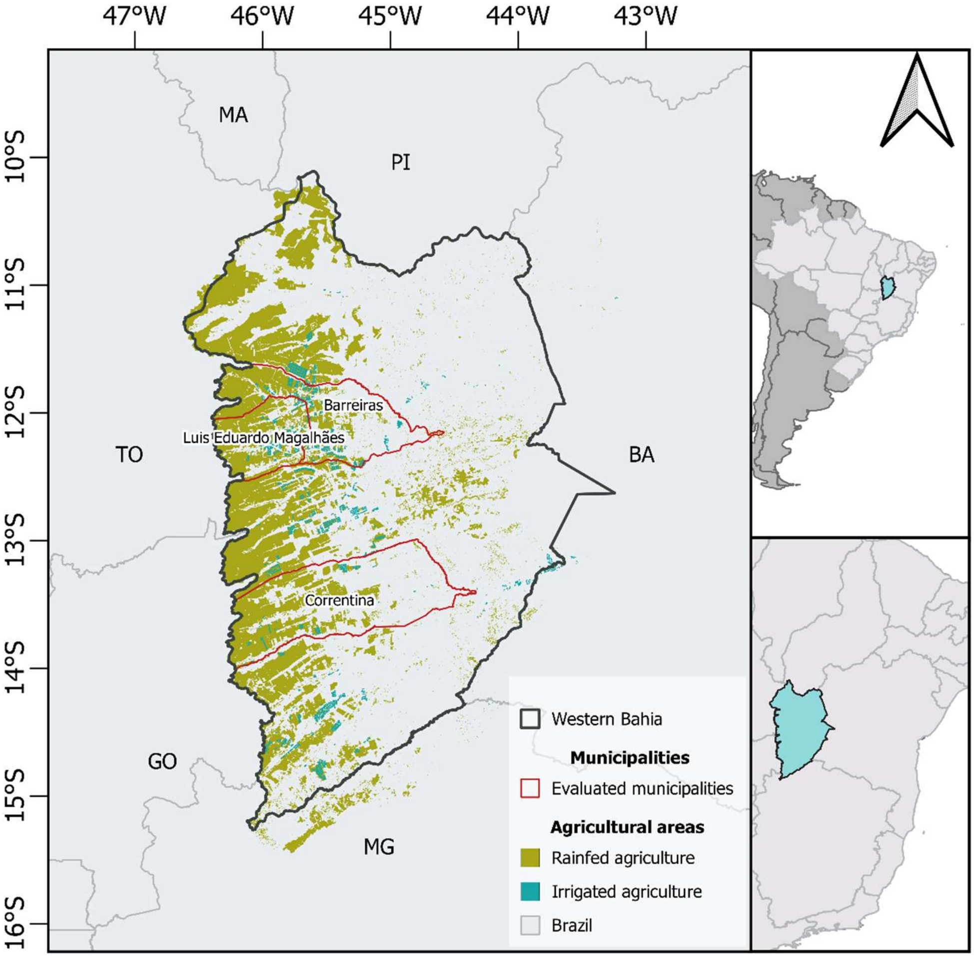
This work aims to evaluate the impact of adopting the rainy season onset forecast on the rainfed and irrigated economic data.

2.3. MATERIALS AND METHODS

2.3.1. Study location

Western Bahia is part of the region treated as the world´s most active agricultural frontier, MATOPIBA. In Western Bahia (Figure 17), the municipalities of Barreiras, Correntina, and Luís Eduardo Magalhães are highly representative in regional agricultural production, especially with cotton, bean, maize, and soybean, which represent on average 94% of the agricultural production value of these municipalities. The climate of these municipalities is type Aw according to the Köppen classification system, e.g., tropical with a dry season in the winter. Barreiras has 1045 mm annual mean rainfall, Correntina has 939 mm, and Luís Eduardo Magalhães has 1511 mm.

Figure 17 - General view of Western Bahia, representing the municipalities of Barreiras, Correntina and Luis Eduardo Magalhães and irrigated and rainfed areas identified for 2019.



2.3.2. Data

Observed yield data were obtained through direct interviews with farmers and the Irriger Connect® database (Brazil's name for the Valley Scheduling software). The data represent 20 farms in Western Bahia between 2011 to 2020 for cotton and soybean crops under irrigated and rainfed conditions, and beans and maize under rainfed conditions. This database represents a cultivated area of 110,475.85 hectares.

Reference evapotranspiration (ETo, mm day^{-1}) (ALLEN et al., 1998) and rainfall (mm day^{-1}) data were obtained through the SISDAGRO platform (INMET, 2021) for the years 2011 to 2020. Seeding dates range was obtained from agroclimatic evaluation by CONAB (2019).

Unitary value of agricultural production (R$ kg^{-1}) was obtained from the Survey of Municipal Agricultural Production by the Brazilian Institute of Geography and Statistics (IBGE, 2021) as the ratio between the production value and amount produced. Production cost per area was obtained from the Survey of Agricultural Production Costs by CONAB (2021). Irrigation cost was obtained from Irriger Connect energy reports.

2.3.3. Crop simulation

Crop simulation was done using IrriPlus® software (2008). Potential crop evapotranspiration (ETcP, mm day^{-1}) is the product of ETo by the crop coefficient (Kc, adimensional) and the location coefficient (Kl, adimensional). Crop phases, their respective Kc, and the total crop cycle duration are presented in Table 5. Adopted Kl was equal to 1, representing a center pivot irrigation system.

Table 5 - Adopted crop coefficient and phases duration for cotton, bean, maize, and soybean.

Crop	Kc initial	Kc average	Kc final	Duration (Days)
Cotton	0.4	1.05	0.8	130
Bean	0.2	1	0.7	120
Maize	0.4	1.13	0.85	130
Soybean	0.35	1.07	0.75	110

Actual crop evapotranspiration (ETc, mm day^{-1}) is the product of ETcP and water availability coefficient (Ks, dimensionless quantity). Ks was calculated as proposed by Bernardo *et al*. (2019) mathematically described by Equation 6:

$$\mathrm{Ks} = \frac{\log_n \times (LAA + 1)}{\log_n \times (CTA + 1)} \tag{6}$$

where LAA (mm) is the current soil's water depth, and CTA (mm) is the total capacity of water in the soil.

To better represent the study regions, we assumed a soil depth equal to 0.60 m with 15% field capacity and 7% wilting point for Barreiras and Correntina. For Luís Eduardo Magalhães, it was considered 0.60 m of soil depth, 20% field capacity, and 10% wilting point.

The number of simulations per year was defined to maximize the growing season's representativeness, considering the range of seeding dates. The seeding time range, number of simulations per year, and the interval between seedings adopted for each crop can be seen in Table 6.

Table 6 – Seeding time range, number of simulations per year, and the interval between seeding for evaluated crops.

Crop	Seeding time range (fortnight-month)	Simulations per year	Interval between seeding (days)
Cotton	1-11 to 2-02	40	3
Bean 1° crop	1-10 to 2-02	50	3
Bean 2° crop	1-04 to 2-06	30	3
Maize 1° crop	1-10 to 2-02	50	3
Maize 2° crop	1-05 to 2-06	20	3
Soybeans	1-10 to 2-02	40	3

Possible crop rotation combinations were defined by adjusting the planting schedule. For each rotation combination, nine simulations were performed. These simulations consider the advance and delay (1 to 4 fortnightly) and the original rainfall conditions, representing a possible response to the rainy season onset forecast. The crop occupation period of each of the adopted rotation combinations can be seen in Table 7.

Table 7 – Occupation period for each crop in crop rotation model.

Crop rotation	1° crop occupation	2° crop occupation	3° crop occupation
Bean-Maize	09/08 - 07/12	12/12 - 21/04	-
Bean-Cotton	09/08 - 07/12	12/12 - 21/04	-
Bean-Soybean	09/08 - 07/12	12/12 - 01/04	-
Bean-Soybean-Maize	09/08 - 07/12	12/12 - 01/04	06/04 - 14/08
Maize-Bean	09/08 - 17/12	22/12 - 21/04	-
Cotton-Bean	25/07 - 02/12	07/12 - 06/04	-
Cotton-Maize	25/07 - 02/12	07/12 - 16/04	-
Soybean-Bean	09/08 - 27/11	02/12 - 01/04	-
Soybean-Maize	09/08 - 27/11	02/12 - 11/04	-
Soybean-Maize-Bean	09/08 - 27/11	02/12 - 11/04	16/04 - 14/08
Soybean-Maize-Cotton	09/08 - 27/11	02/12 - 11/04	16/04 - 24/08
Soybean-Cotton	09/08 - 27/11	02/12 - 11/04	-

The simulations were configured to represent the rainfed conditions with the soil's water balance considering only the rainfall and the irrigated condition, with rainfall and irrigation as water inputs. The strategy adopted to simulate the irrigation decision was to control the water deficit by irrigating at point “f”. The point “f” represents the soil safety moisture and can be calculated in IrriPlus software using the factors 0.6, adopted for cotton and maize, and 0.5, adopted for beans and soybeans.

The simulations have output variables soil moisture, ETcP, ETc, rainfall, and irrigation depth. Cotton 1° and 2° crop as bean 1° and 2° crop data were grouped in the same dataset.

2.3.4. Estimated crop yield

Actual crop yield was calculated as proposed by Steduto *et al.* (2012) in the original FAO water production function been described in Equation 7, in an adapted form to highlight the actual crop yield as isolated output.

$$Ya = -(Yx \times Ky) + \left(\frac{ETa \times Yx \times Ky}{ETx}\right) + Yx \tag{7}$$

where Ya (kg ha^{-1}) is the actual crop yield, Yx (kg ha^{-1}) is the maximum crop yield, Ky (adimensional) is a yield response factor, ETa (mm day^{-1}) is the actual evapotranspiration, and ETx (mm day^{-1}) is the maximum evapotranspiration. The maximum crop yield was obtained from the survey of observed yields. Adopted Ky values were 0.85, 1.15, 1.25, and 0.85 for cotton, bean, maize, and soybean, respectively. Adopted ETx was considered as the amount of ETcP and Eta as the amount of ETc.

2.3.5. Water productivity

Considering one hectare, water productivity (WP, kg m^{-3}) is the ratio between actual crop yield (Ya) and total water inputs during the crop cycle (WBI, m^3 – Equation 8). For rainfed conditions, the only water input is rainfall. In irrigated conditions, water input is the sum of rainfall and irrigation.

$$\mathrm{WP} = \frac{Ya}{WBI} \tag{8}$$

2.3.6. Gross profit

Gross profit (GP, R$ ha^{-1}) from the agricultural activity is the difference between the sum of revenues (REV, R$) and the sum of costs (SC) (Equation 9).

$$\mathrm{GP} = \sum REV - \sum SC \tag{9}$$

REV was calculated as the product between the unitary value of agricultural production (R\$ kg^{-1}) and the crop yield (Ya). The cost of agricultural activity for rainfed areas was considered as the production cost per area (R\$ ha^{-1}). In contrast, for irrigated areas, in addition to this it was also considered the irrigation cost. Irrigation cost is the product between the irrigation depth (mm) and the irrigation unitary cost (R\$ mm^{-1} ha^{-1}).

Adopted values for unitary value of agriculture production are 2.43 R\$ kg^{-1}, 2.26 R\$ kg^{-1}, 0.45 R\$ kg^{-1} and 0.98 R\$ kg^{-1} in Barreiras, 2.23 R\$ kg^{-1}, 1.83 R\$ kg^{-1}, 0.49 R\$ kg^{-1}, and 1.02 R\$ kg^{-1} in Correntina and 2.46 R\$ kg^{-1}, 2.12 R\$ kg^{-1}, 0.46 R\$ kg^{-1} and 1.01 R\$ kg^{-1} in Luís Eduardo Magalhães for cotton, bean, maize, and soybean, respectively. Production cost per area was considered uniform in all counties as 6794.55 R\$ ha^{-1} , 1770.91 R\$ ha^{-1}, 3886.30 R\$ ha^{-1} and 2630.01 R\$ ha^{-1} for cotton, bean, maize, and soybean, respectively. Irrigation unitary cost was considered as R\$ 2.10 mm^{-1} ha^{-1}.

2.3.7. Water profitability

Water profitability (WPr, R\$ m^{-3}) was assessed as the ratio between gross profit and the water balance inputs, being mathematically described by Equation 10.

$$\mathrm{WPr} = \frac{GP}{WBI} \tag{10}$$

2.3.8. Statistical analysis

Average results of Ya, WP, GP and WPr were submitted to analysis of variance (ANOVA) and for least significant difference (LSD) test with alpha value equal to 0.05. ANOVA and LSD test the tests were conducted to demonstrate the differences for each crop, in each municipality. Variation factors for each analysis are the evaluated years (2012 to 2020) and the condition water supply (irrigated and rainfed). Repetitions are the number of simulations per year, described in Table 6. The null hypothesis means that there is no variation in the results in the years and conditions evaluated, while the hypothesis determines that there is a difference in these results.

2.3.9. Comparative analysis

Comparative analyses were done first to demonstrate the equivalence between irrigated and rainfed areas. For this purpose, the irrigated area equivalence (IAE, hectares of irrigated area per hectares of rainfed area) index was calculated. IAE is the ratio between the REV of irrigated areas and the REV of rainfed areas.

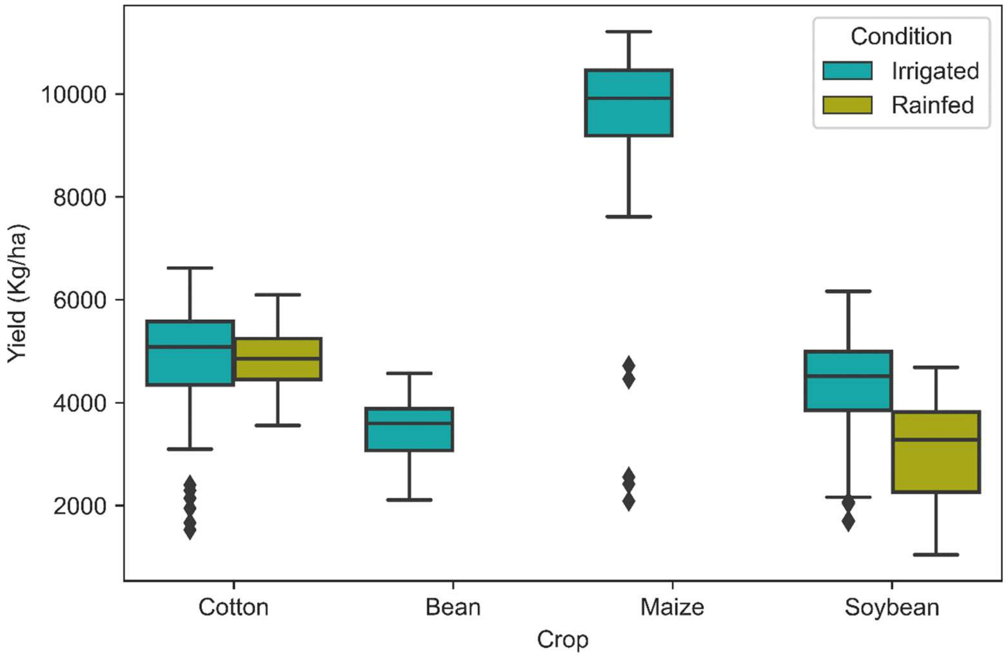
Secondly, the REV increments considering the best seeding date were calculated by the ratio between the maximum REV and average REV for irrigated and rainfed areas.

2.4. RESULTS

2.4.1. Crop yield

The observed maximum and average crop yield values and the sample standard deviation were respectively: 6615.90 kg ha^{-1}, 4926.99 kg ha^{-1}, and 914.35 kg ha^{-1} for irrigated cotton; 6098.84 kg ha^{-1}, 4804.07 kg ha^{-1}, and 715.61 kg ha^{-1} for rainfed cotton; 4570.80 kg ha^{-1}, 3469.83 kg ha^{-1}, and 594.13 kg ha^{-1} for irrigated bean; 11212.20 kg ha^{-1}, 9238.45 kg ha^{-1} and 2202.26 kg ha^{-1} for irrigated maize; 6165.42 kg ha^{-1}, 4366.64 kg ha^{-1} and 844.58 kg ha^{-1} for irrigated soybean and 4689.69 kg ha^{-1}, 3021.39 kg ha^{-1} and 958.84 kg ha^{-1} for rainfed soybean. Data distribution is summarized in Figure 18.

Figure 18 - Observed crop yields for Western Bahia.

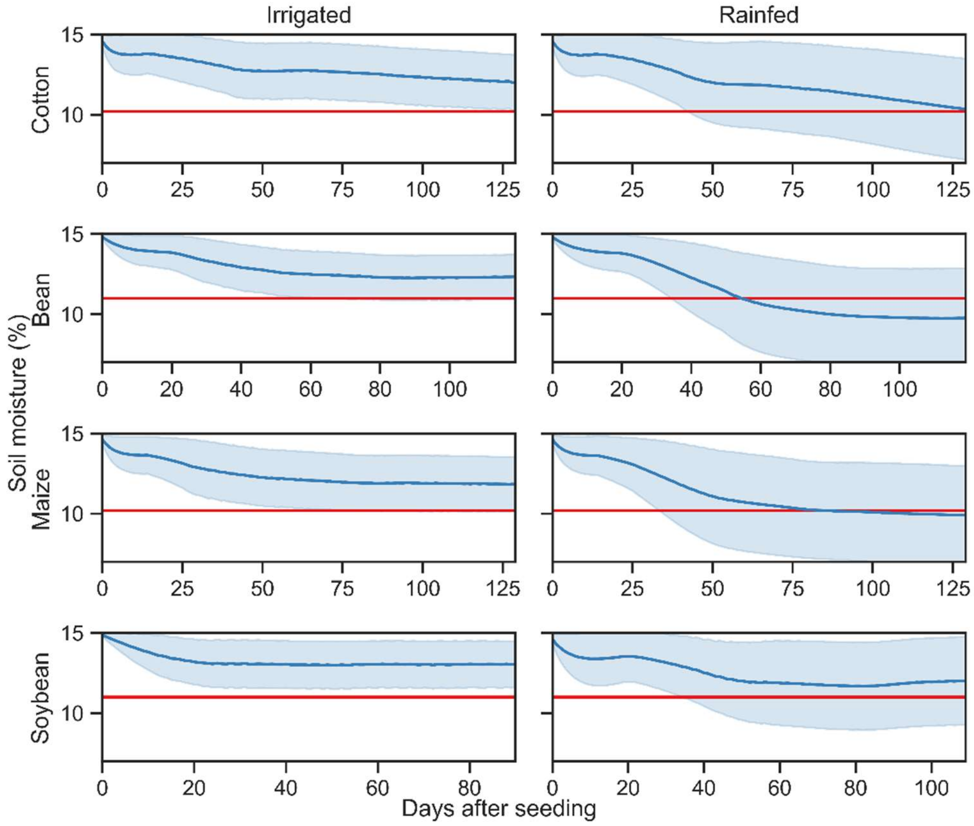


2.4.2. Soil moisture

2.4.2.1. Barreiras

For Barreiras, the average behavior and deviations of soil moisture (Figure 19) for all crops evaluated under irrigated conditions remain above the “f” point adopted for the soil, indicating that an eventual water deficit would not affect crop yields considerably. Differently, for cotton and soybeans under rainfed conditions, even if the average soil moisture remains above the “f” point, due to the average humidity behavior, a considerable water deficit is expected from 40 days after planting for both crops. For bean and maize under rainfed conditions, both the average behavior and the standard deviation of the soil moisture simulated results also indicate a water deficit starting from 35 days after planting for both crops.

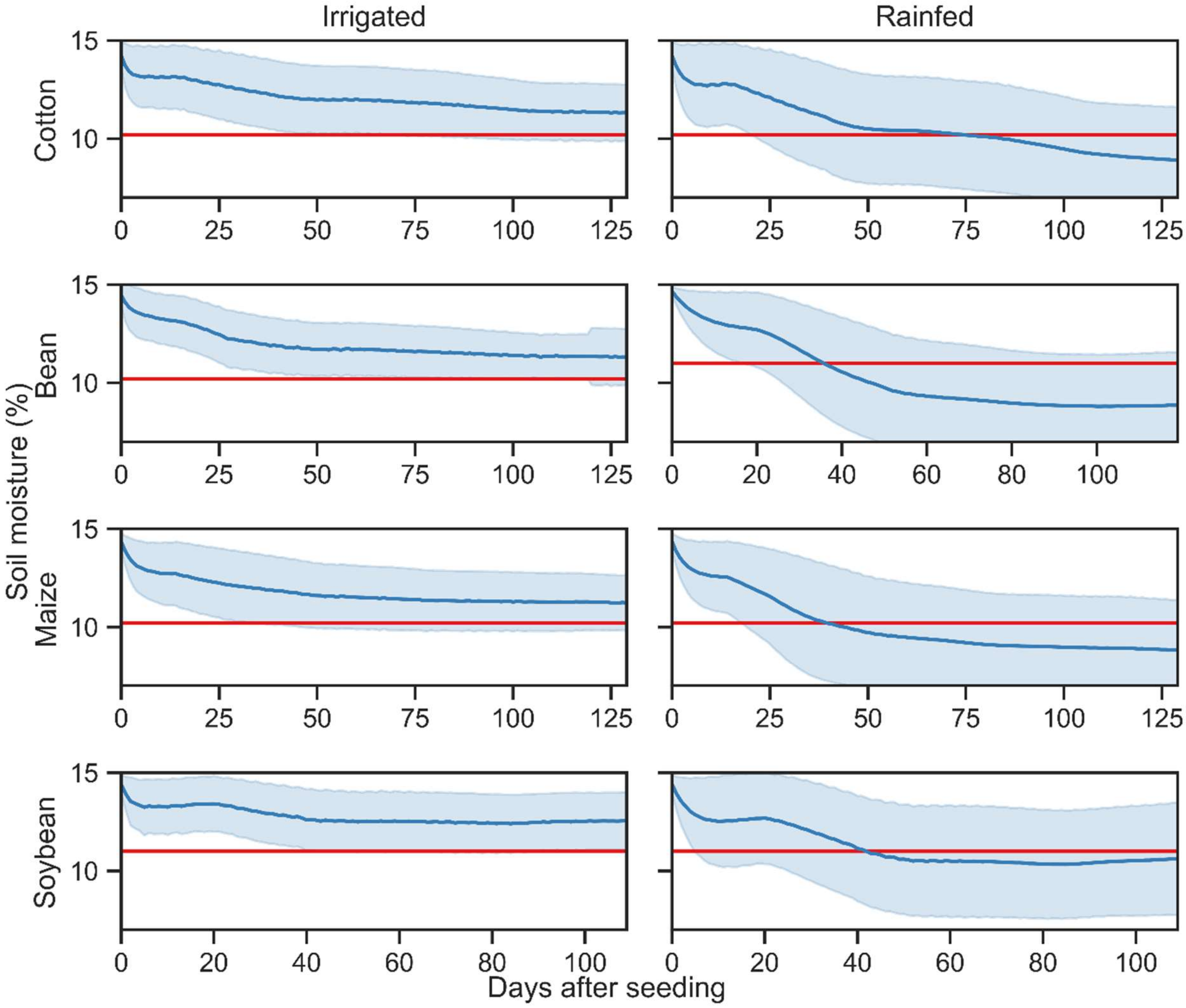
Figure 19 – Average behavior and standard deviation of soil moisture over cotton, beans, maize, and soybean crop season, simulated in irrigated and rainfed conditions for the municipality of Barreiras-BA. The blue line represents the mean, while the blue shade represents the standard deviation. The red line represents the soil’s “f” point, depending on the point f adopted for each crop. The upper and lower limits of the vertical axis represent the field capacity and the wilting point adopted for the considered soils. The horizontal axis represents the days after crop seeding.



2.4.2.2. Correntina

For Correntina, the average and deviations of soil moisture (Figure 20), for all evaluated crops under irrigated conditions, remain above the “f” point, same as observed for Barreiras, which also indicates a good humidity condition during the crop season. Conversely, for all crops under rainfed conditions, soil moisture’s average and deviation indicate a considerable water deficit, after the corresponding period to crop’s vegetative development, flowering, and final phase.

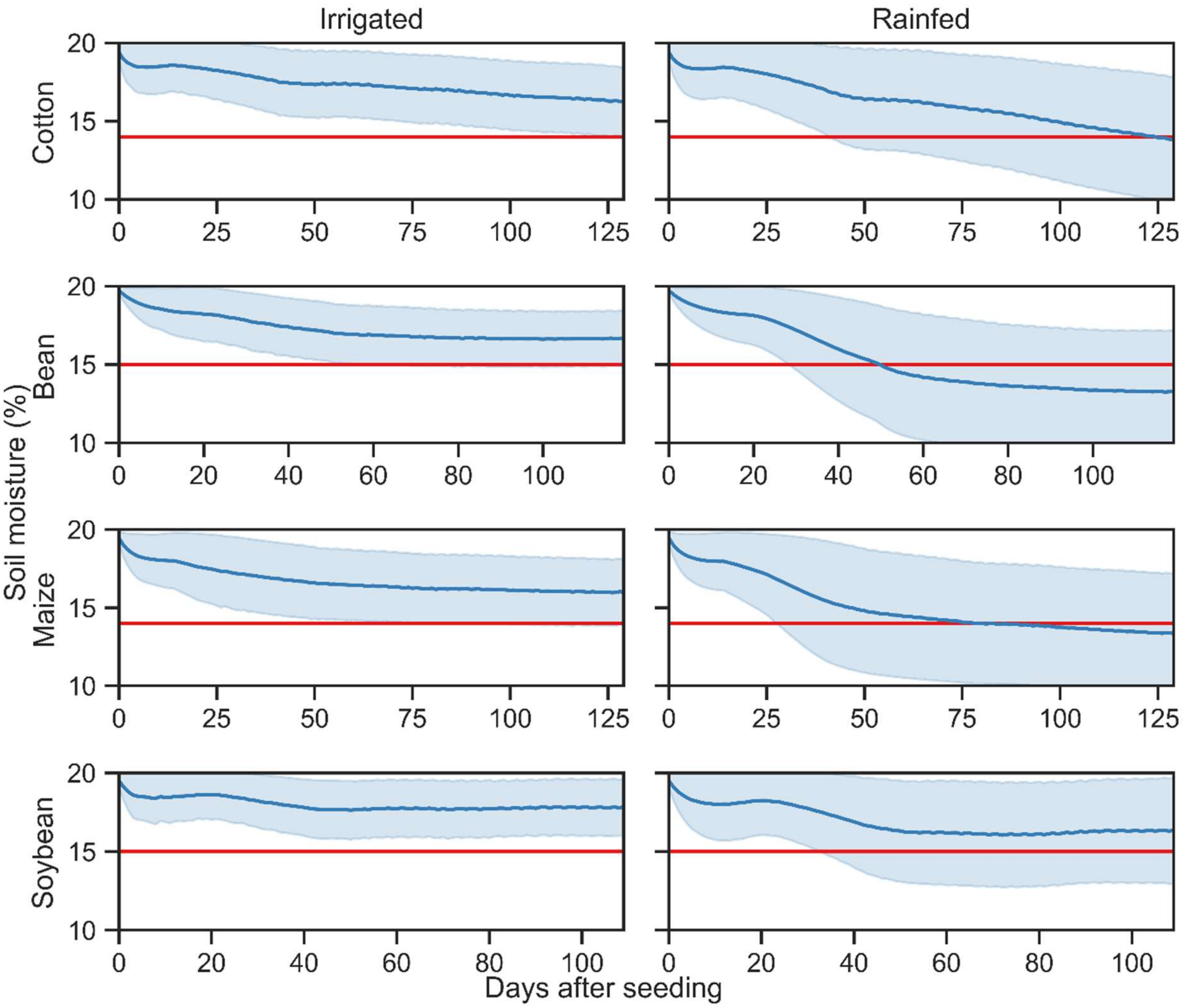
Figure 20 – As in Figure 19, but for Correntina.



2.4.2.3. Luís Eduardo Magalhães

Soil moisture maintains the same behavior for irrigated crops as seen in Barreiras and Correntina, only varying in rainfed conditions. In this case, a significant water deficit is also expected for beans and maize, especially after 30 days from seeding. During the cotton growing season, the average soil moisture value indicates a considerable water deficit close to the harvest phase. For soybean, the same variable indicates only minor water deficits during the entire growing season. Anyway, for cotton and soybean, soil moisture standard deviation indicates that water deficit can be remarkable, depending on climate conditions during the growing season.

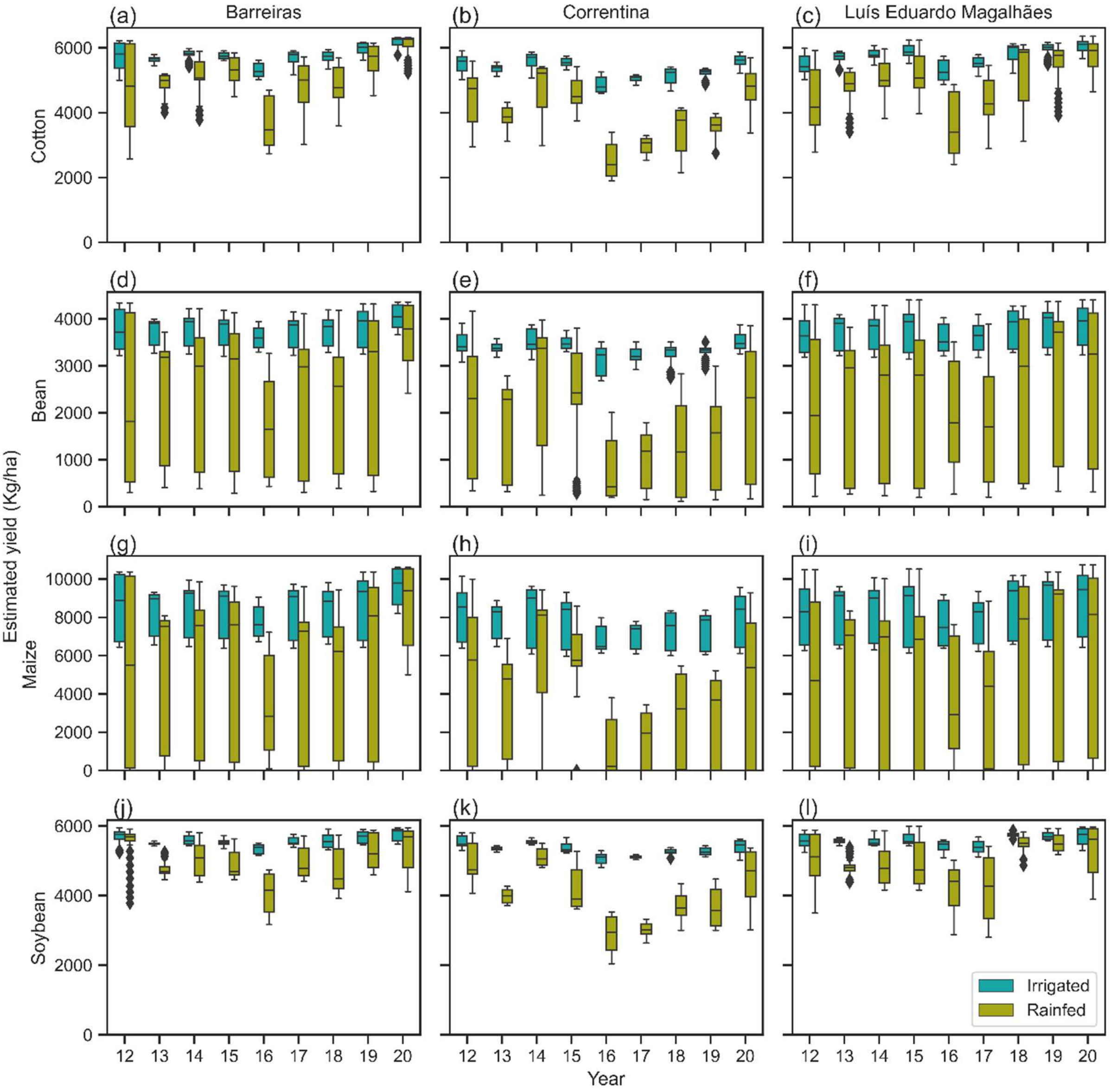
Figure 21 - As in Figure 19, but for Luis Eduardo Magalhães.



2.4.3. Estimated crop yield

Figure 22 shows the estimated crop yield of cotton, bean, maize, and soybean for Barreiras, Correntina, and Luis Eduardo Magalhães between 2012 and 2020. An initial analysis of these data reveals three main characteristics.

Figure 22 - Estimated distribution of cotton bean, maize, and soybean yield during the years 2012 to 2020, under irrigated and rainfed conditions, for the municipalities of Barreiras, Correntina, and Luis Eduardo Magalhães.



First, crop yield in rainfed areas may be similar to yields in irrigated areas when rainfall conditions are appropriate. For example, maximum potential yields are similar in both rainfed and irrigated areas for all crops and all municipalities in 2012 and 2020.

Second, in drier years like 2016, harvest losses in rainfed areas were more evident than under irrigated conditions. On the other hand, this yield loss is continuously observed in Correntina between 2016 and 2019 for all crops.

Finally, harvest losses can be significant in all evaluated years for beans and cotton, especially when these crops are cultivated as the second crop in double-cropping systems.

The ANOVA showed that for the conditions and the years, as well as for the interaction of these factors, there is a difference between the calculated average data. Results of the LSD test for assessed year and condition of each crop in each county, as well as the estimated average productivity values can be verified in Table 8. For average values, the same characteristics as the visual analysis of Figure 22 can be observed.

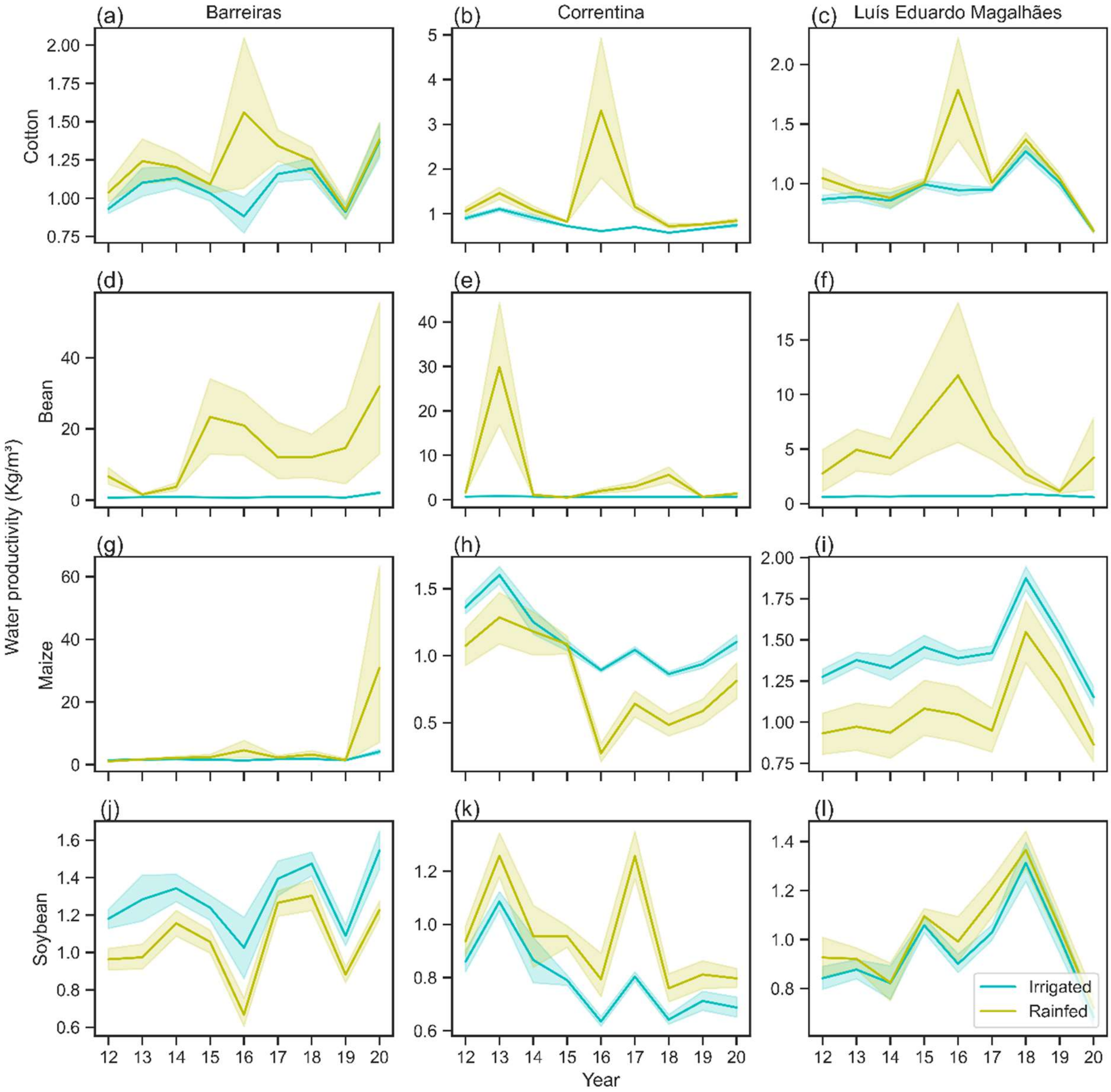
Table 8 – Average estimated yield values for cotton, beans, maize, and soybean, under irrigated and rainfed conditions, at Barreiras, Correntina, and Luís Eduardo Magalhães, between 2012 and 2020. Numbers followed by the same letters are not significantly different (α=0.05).

County	Crop	Condition	2012	2013	2014	2015	2016	2017	2018	2019	2020
Barreiras	Cotton	Irrigated	5,739 ^{c}	5,651 ^{c}	5,802 ^{bc}	5,755 ^{c}	5,303 ^{d}	5,689 ^{c}	5,720 ^{c}	5,980 ^{ab}	6,173 ^{a}
		Rainfed	4,733 ^{e}	4,908 ^{e}	5,135 ^{d}	5,314 ^{d}	3,680 ^{f}	4,807 ^{e}	4,855 ^{e}	5,637 ^{c}	6,087 ^{a}
	Bean	Irrigated	3,771 ^{ab}	3,728 ^{b}	3,776 ^{ab}	3,753 ^{ab}	3,602 ^{b}	3,718 ^{b}	3,743 ^{ab}	3,822 ^{ab}	4,044 ^{a}
		Rainfed	2,198 ^{d}	2,317 ^{cd}	2,380 ^{cd}	2,438 ^{cd}	1,668 ^{e}	2,152 ^{d}	2,206 ^{d}	2,593 ^{c}	3,645 ^{b}
	Maize	Irrigated	8,611 ^{bc}	8,428 ^{bc}	8,619 ^{bc}	8,530 ^{bc}	7,825 ^{c}	8,448 ^{bc}	8,457 ^{bc}	8,811 ^{ab}	9,583 ^{a}
		Rainfed	5,365 ^{e}	5,514 ^{e}	5,750 ^{de}	5,925 ^{de}	3,484 ^{f}	5,157 ^{e}	5,112 ^{e}	6,389 ^{d}	8,497 ^{bc}
	Soybean	Irrigated	5,701 ^{ab}	5,493 ^{de}	5,602 ^{bcd}	5,530 ^{cd}	5,337 ^{ef}	5,562 ^{bcd}	5,564 ^{bcd}	5,679 ^{abc}	5,766 ^{a}
		Rainfed	5,457 ^{de}	4,760 ^{hi}	5,051 ^{g}	4,893 ^{gh}	4,055 ^{j}	4,958 ^{g}	4,703 ^{i}	5,266 ^{f}	5,361 ^{ef}
Correntina	Cotton	Irrigated	5,507 ^{ab}	5,361 ^{bc}	5,621 ^{a}	5,555 ^{a}	4,857 ^{e}	5,053 ^{d}	5,131 ^{d}	5,223 ^{cd}	5,606 ^{a}
		Rainfed	4,424 ^{g}	3,873 ^{h}	4,750 ^{ef}	4,629 ^{f}	2,529 ^{k}	2,989 ^{j}	3,434 ^{i}	3,590 ^{i}	4,762 ^{ef}
	Bean	Irrigated	3,467 ^{abc}	3,388 ^{abc}	3,527 ^{a}	3,492 ^{ab}	3,120 ^{d}	3,223 ^{cd}	3,265 ^{bcd}	3,314 ^{abcd}	3,520 ^{ab}
		Rainfed	2,094 ^{f}	1,658 ^{g}	2,544 ^{e}	2,409 ^{e}	788 ^{j}	1,052 ^{i}	1,278 ^{hi}	1,437 ^{gh}	2,021 ^{f}
	Maize	Irrigated	8,252 ^{a}	7,910 ^{ab}	8,259 ^{a}	7,942 ^{ab}	6,878 ^{c}	7,116 ^{c}	7,339 ^{bc}	7,427 ^{bc}	8,083 ^{a}
		Rainfed	5,015 ^{e}	3,738 ^{f}	6,208 ^{d}	6,013 ^{d}	1,219 ^{h}	1,785 ^{h}	2,732 ^{g}	2,983 ^{g}	4,758 ^{e}
	Soybean	Irrigated	5,547 ^{a}	5,348 ^{b}	5,547 ^{a}	5,374 ^{b}	5,063 ^{d}	5,111 ^{cd}	5,255 ^{bc}	5,267 ^{b}	5,397 ^{ab}
		Rainfed	4,982 ^{d}	3,979 ^{g}	5,103 ^{d}	4,199 ^{f}	2,877 ^{i}	3,002 ^{i}	3,729 ^{h}	3,655 ^{h}	4,523 ^{e}
Luís Eduardo Magalhães	Cotton	Irrigated	5,487 ^{de}	5,706 ^{cd}	5,807 ^{bc}	5,911 ^{abc}	5,289 ^{ef}	5,528 ^{de}	5,839 ^{abc}	5,959 ^{ab}	6,064 ^{a}
		Rainfed	4,356 ^{h}	4,797 ^{g}	5,082 ^{f}	5,209 ^{f}	3,616 ^{i}	4,353 ^{h}	5,182 ^{f}	5,526 ^{de}	5,777 ^{bc}
	Bean	Irrigated	3,660 ^{a}	3,714 ^{a}	3,741 ^{a}	3,773 ^{a}	3,573 ^{a}	3,619 ^{a}	3,805 ^{a}	3,825 ^{a}	3,860 ^{a}
		Rainfed	2,179 ^{cd}	2,116 ^{cd}	2,256 ^{cd}	2,288 ^{cd}	1,933 ^{de}	1,765 ^{e}	2,435 ^{bc}	2,755 ^{b}	2,663 ^{b}
	Maize	Irrigated	8,229 ^{abc}	8,404 ^{abc}	8,480 ^{abc}	8,571 ^{abc}	7,706 ^{c}	7,969 ^{bc}	8,692 ^{ab}	8,855 ^{ab}	8,910 ^{a}
		Rainfed	4,975 ^{f}	5,146 ^{f}	5,450 ^{f}	5,575 ^{ef}	3,689 ^{g}	3,987 ^{g}	5,877 ^{def}	6,612 ^{d}	6,491 ^{de}
	Soybean	Irrigated	5,589 ^{abc}	5,568 ^{abc}	5,570 ^{abc}	5,635 ^{ab}	5,421 ^{cd}	5,404 ^{cd}	5,743 ^{a}	5,719 ^{a}	5,699 ^{ab}
		Rainfed	5,072 ^{e}	4,821 ^{f}	4,872 ^{f}	4,913 ^{ef}	4,203 ^{g}	4,197 ^{g}	5,508 ^{bc}	5,507 ^{bc}	5,282 ^{d}

2.4.4. Water productivity

Figure 23 shows the water productivity of cotton, bean, maize, and soybean for Barreiras, Correntina, and Luis Eduardo Magalhães between 2012 and 2020. Due graph scale, some values cannot be displayed clearly, for example in subdivision b, d, e, f, and g.

Figure 23 – Water productivity of cotton bean, maize, and soybean yield during the years 2012 to 2020, under irrigated and rainfed conditions, for the municipalities of Barreiras, Correntina, and Luis Eduardo Magalhães. Lines represent the mean, while the shaded area represents the standard deviation.



Rainfed areas present in general, higher values of water productivity than irrigated, except for maize in Correntina (Figure 23, h) and Luís Eduardo Magalhães (Figure 23, i), and soybean in Barreiras (Figure 23, j). In general, in the same years in which crop losses are more significant for rainfed areas, maximum values are observed for rainfed areas, and minimum values are observed for irrigated areas, as example for cotton in Barreiras, Correntina, and Luis Eduardo Magalhães (Figure 23, a, b, and c).

ANOVA result shows significant differences between the irrigated and rainfed conditions, as well as for the years evaluated and for the interactions of these factors for each crop in each municipality. The average values, as well as the result of the LSD test can be seen in Table 9.

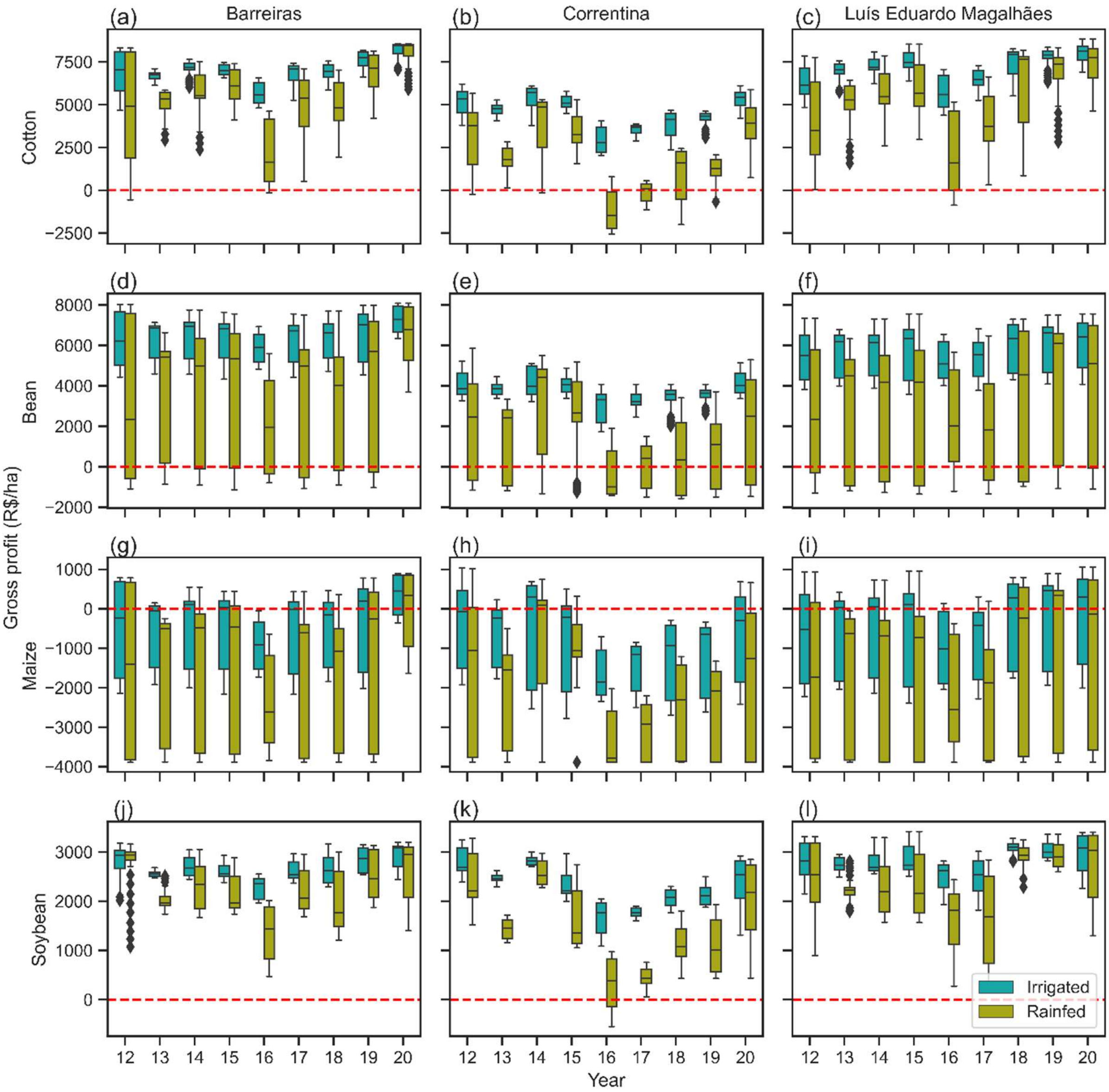
Table 9 – Average water productivity values for cotton, beans, maize, and soybean, under irrigated and rainfed conditions, at Barreiras, Correntina and Luís Eduardo Magalhães, between 2012 and 2020. Numbers followed by the same letters are not significantly different (α=0.05).

County	Crop	Condition	2012	2013	2014	2015	2016	2017	2018	2019	2020
Barreiras	Cotton	Irrigated	0.93 fgh	1.10 defg	1.13 def	1.03 efgh	0.88 h	1.16 cde	1.20 bcde	0.91 gh	1.37 ab
		Rainfed	1.04 efgh	1.24 bcd	1.20 bcde	1.09 defg	1.56 a	1.34 bc	1.25 bcd	0.92 gh	1.38 ab
	Bean	Irrigated	0.70 g	0.81 g	0.86 g	0.76 g	0.73 g	0.85 g	0.90 g	0.71 g	2.06 efg
		Rainfed	6.63 defg	1.57 fg	3.70 efg	23.36 ab	20.96 bc	inf cdef	12.05 cde	14.64 bcd	31.84 a
	Maize	Irrigated	1.41 b	1.64 b	1.73 b	1.59 b	1.36 b	1.75 b	1.82 b	1.43 b	4.14 b
		Rainfed	1.09 b	1.68 b	2.17 b	2.37 b	4.59 b	2.24 b	3.25 b	1.48 b	30.85 a
	Soybean	Irrigated	1.18 efg	1.28 cde	1.34 cd	1.24 def	1.03 ij	1.39 bc	1.47 ab	1.09 ghi	1.54 a
		Rainfed	0.96 jk	0.97 ijk	1.16 fgh	1.06 hij	0.67 l	1.27 def	1.30 cd	0.88 k	1.23 def
Correntina	Cotton	Irrigated	0.90 cd	1.10 bcd	0.91 cd	0.72 cd	0.61 d	0.70 cd	0.58 d	0.66 cd	0.74 cd
		Rainfed	1.06 bcd	1.46 b	1.08 bcd	0.82 cd	3.30 a	1.15 bc	0.72 cd	0.76 cd	0.84 cd
	Bean	Irrigated	0.72 b	0.79 b	0.73 b	0.66 b	0.60 b	0.64 b	0.60 b	0.63 b	0.67 b
		Rainfed	1.63 b	29.86 a	1.08 b	0.50 b	1.99 b	2.98 b	5.60 b	0.69 b	1.37 b
	Maize	Irrigated	1.36 a	1.60 ab	1.25 a	1.08 ab	0.89 c	1.04 c	0.86 bc	0.94 bc	1.10 a
		Rainfed	1.07 e	1.29 f	1.18 d	1.09 d	0.27 h	0.64 h	0.48 g	0.59 g	0.81 e
	Soybean	Irrigated	0.86 de	1.09 b	0.87 de	0.79 efg	0.63 i	0.80 ef	0.64 i	0.71 ghi	0.69 hi
		Rainfed	0.94 cd	1.26 a	0.96 c	0.96 c	0.79 efg	1.26 a	0.76 fgh	0.81 ef	0.80 ef
Luís Eduardo Magalhães	Cotton	Irrigated	0.87 d	0.89 cd	0.86 d	0.99 cd	0.94 cd	0.95 cd	1.27 b	1.01 cd	0.60 e
		Rainfed	1.05 c	0.95 cd	0.88 cd	1.01 cd	1.79 a	1.01 cd	1.37 b	1.04 c	0.60 e
	Bean	Irrigated	0.63 e	0.67 e	0.66 e	0.69 e	0.70 e	0.72 e	0.89 e	0.74 e	0.59 e
		Rainfed	2.77 de	4.94 cd	4.18 cd	7.95 b	11.74 a	6.24 bc	2.73 de	1.15 e	4.22 cd
	Maize	Irrigated	1.28 ef	1.38 cde	1.33 de	1.46 bcd	1.39 bcde	1.42 bcde	1.87 a	1.54 bc	1.15 fg
		Rainfed	0.93 hi	0.97 hi	0.94 hi	1.08 gh	1.05 gh	0.95 hi	1.55 b	1.26 ef	0.86 i
	Soybean	Irrigated	0.84 fg	0.88 fg	0.82 g	1.06 cd	0.90 fg	1.03 cd	1.31 a	1.01 cde	0.68 h
		Rainfed	0.93 ef	0.92 ef	0.82 g	1.10 bc	0.99 de	1.17 b	1.37 a	1.05 cd	0.72 h

2.4.5. Gross profit

Figure 24 shows the gross profit of cotton, bean, maize, and soybean for Barreiras, Correntina, and Luis Eduardo Magalhães between 2012 and 2020. Despite the higher cost of production, irrigated areas have greater profit potential compared to rainfed areas. Cotton rainfed areas are more likely to suffer losses, especially in years of severe water deficit. The same is notable for beans and maize, especially when they grow as a second crop in double-cropping systems.

Figure 24 – Gross profit of cotton, beans, maize, and soybean during the years 2012 to 2020, under irrigated and rainfed conditions, for the municipalities of Barreiras, Correntina, and Luis Eduardo Magalhães. The red dashed line represents the limit between profit and loss.



Even under irrigated conditions, maize can present a considerable monetary loss, considering its lower market value compared to other crops. Soybean presented possibilities of losses depending on the date of planting in Correntina in 2016.

ANOVA result shows significant differences between the irrigated and rainfed conditions and the years evaluated, and the interactions between these factors for each crop in each municipality (Table 10).

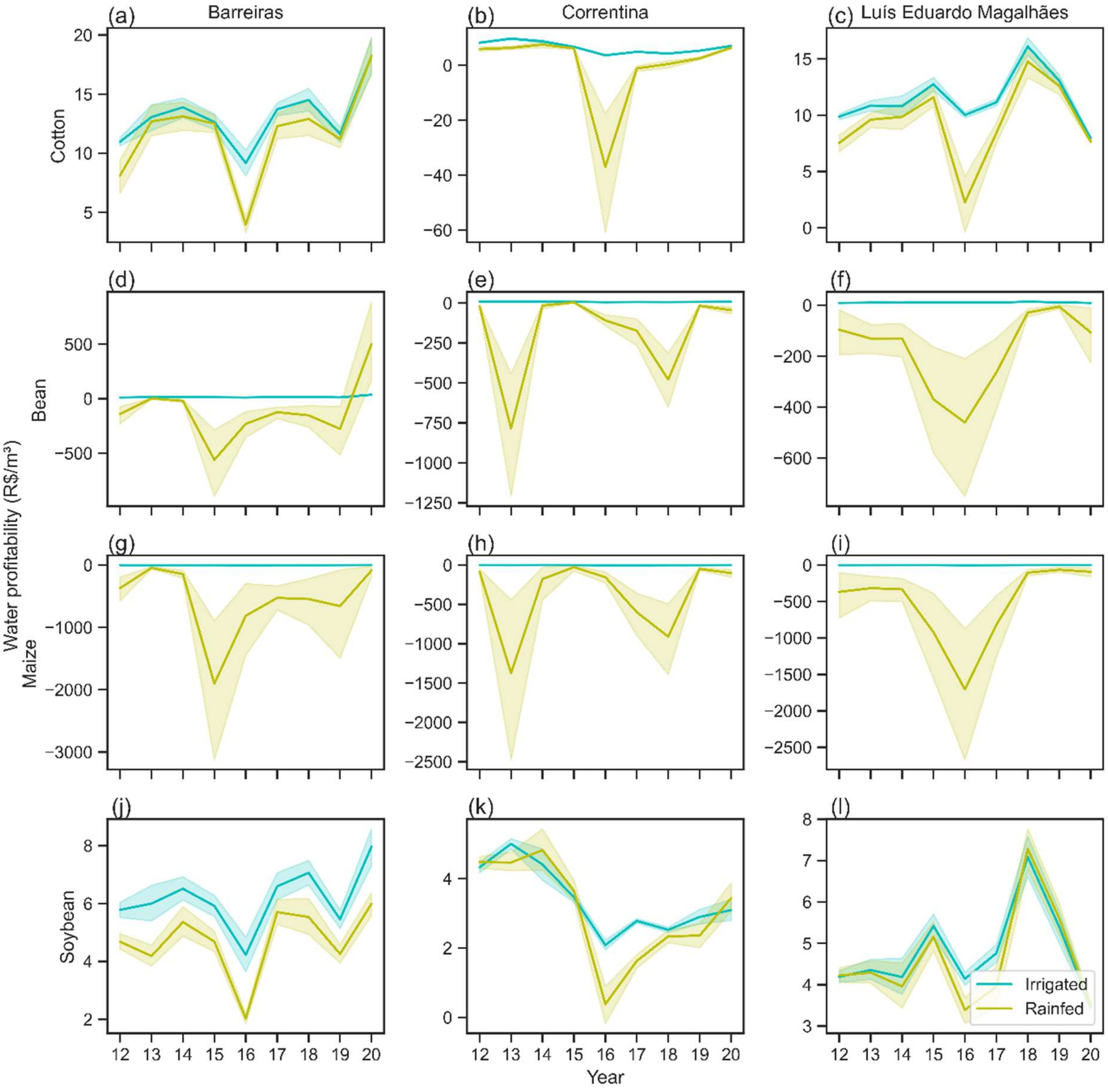
Table 10 – Average water productivity values for cotton, bean, maize, and soybean, under irrigated and rainfed conditions, at Barreiras, Correntina, and Luís Eduardo Magalhães, between 2012 and 2020.

County	Crop	Condition	2012		2013		2014		2015		2016		2017		2018		2019		2020	
Barreiras	Cotton	Irrigated	6,870	c	6,717	c	7,129	bc	7,043	c	5,658	de	6,786	c	6,914	c	7,644	ab	8,176	a
		Rainfed	4,706	f	5,133	ef	5,684	d	6,117	d	2,148	f	4,885	f	5,003	f	6,902	c	7,997	a
	Bean	Irrigated	6,289	b	6,261	b	6,392	b	6,331	b	5,871	b	6,196	b	6,299	b	6,514	b	7,283	a
		Rainfed	3,197	d	3,466	cd	3,608	cd	3,739	cd	1,999	e	3,093	d	3,214	d	4,089	c	6,468	b
	Maize	Irrigated	-458	bcd	-482	bcd	-375	bc	-421	bc	-877	de	-506	cd	-467	bcd	-254	bc	344	a
		Rainfed	-1,472	g	-1,405	fg	-1,299	fg	-1,220	efg	-2,318	h	-1,566	g	-1,586	g	-1,011	ef	-63	ab
	Soybean	Irrigated	2,812	abc	2,559	de	2,705	bcd	2,629	de	2,273	f	2,629	de	2,652	cde	2,841	ab	2,948	a
		Rainfed	2,718	bcd	2,035	gh	2,320	f	2,165	fg	1,344	i	2,229	f	1,979	h	2,530	e	2,624	de
Correntina	Cotton	Irrigated	5,135	ab	4,732	b	5,423	a	5,163	ab	2,940	e	3,535	d	3,837	cd	4,185	c	5,314	a
		Rainfed	3,071	e	1,843	f	3,798	cd	3,528	d	-1,154	i	-129	h	863	g	1,211	g	3,826	cd
	Bean	Irrigated	4,047	ab	3,859	abc	4,176	a	4,047	ab	2,986	efg	3,266	def	3,415	cde	3,587	bcd	4,120	a
		Rainfed	2,061	h	1,263	i	2,884	fg	2,637	g	-329	l	153	k	567	jk	858	ij	1,927	h
	Maize	Irrigated	-330	a	-565	abc	-439	ab	-724	bc	-1,636	h	-1,416	fgh	-1,257	efg	-1,135	def	-604	abc
		Rainfed	-1,429	fgh	-2,055	i	-844	cd	-940	cde	-3,289	k	-3,011	k	-2,548	j	-2,424	j	-1,555	gh
	Soybean	Irrigated	2,815	a	2,470	bc	2,820	a	2,356	e	1,659	e	1,769	e	2,071	d	2,129	d	2,382	c
		Rainfed	2,452	bc	1,429	f	2,575	b	1,653	c	305	h	432	h	1,174	g	1,098	g	1,984	d
Luís Eduardo Magalhães	Cotton	Irrigated	6,336	fg	6,970	cde	7,294	bcd	7,578	ab	5,719	h	6,503	efg	7,412	bc	7,737	ab	8,027	a
		Rainfed	3,922	j	5,005	i	5,707	h	6,021	gh	2,101	k	3,913	j	5,953	gh	6,800	def	7,416	bc
	Bean	Irrigated	5,455	ab	5,610	ab	5,711	ab	5,748	ab	5,207	b	5,366	ab	5,929	ab	5,969	a	6,063	a
		Rainfed	2,848	de	2,715	de	3,013	de	3,079	de	2,328	ef	1,972	f	3,391	cd	4,070	c	3,875	c
	Maize	Irrigated	-623	bcd	-489	abcd	-423	abc	-405	abc	-938	defg	-754	cde	-226	ab	-161	ab	-121	a
		Rainfed	-1,598	hi	-1,519	h	-1,379	gh	-1,322	fgh	-2,189	j	-2,052	ij	-1,183	efgh	-845	cde	-901	def
	Soybean	Irrigated	2,838	bcde	2,753	de	2,800	cde	2,876	bcde	2,511	fg	2,511	fg	3,093	a	3,045	ab	2,966	abc
		Rainfed	2,493	gh	2,239	i	2,291	hi	2,332	ghi	1,615	j	1,609	j	2,933	abcd	2,933	abcd	2,705	ef

2.4.6. Water profitability

Figure 25 shows the water profitability of cotton, bean, maize, and soybean for Barreiras, Correntina, and Luis Eduardo Magalhães between 2012 and 2020. Due graph scale, some values cannot be displayed clearly, for example in subdivision b, d, e, f, g, h, i.

Figure 25 – Water profitability of cotton bean, maize, and soybean yield during the years 2012 to 2020, under irrigated and rainfed conditions, for the municipalities of Barreiras, Correntina, and Luis Eduardo Magalhães. Lines represent the mean, while the shaded area represents the standard deviation.



Especially for bean and soybean crops, several negative values are identified for this parameter, indicating again, that the second crop, in continuous cropping system, may have considerable losses due to the marked water deficit.

ANOVA result shows significant differences between the irrigated and rainfed conditions and the years evaluated, and the interactions between these factors for each crop in each municipality (Table 11).

Table 11 – Average water profitability for cotton, bean, maize, and soybean, under irrigated and rainfed conditions, at Barreiras, Correntina, and Luís Eduardo Magalhães, between 2012 and 2020.

County	Crop	Condition	2012	2013	2014	2015	2016	2017	2018	2019	2020
Barreiras	Cotton	Irrigated	10.97 ^{g}	13.06 ^{bcde}	13.89 ^{bc}	12.65 ^{cdef}	9.17 ^{h}	13.72 ^{bcd}	14.50 ^{b}	11.62 ^{efg}	18.22 ^{a}
		Rainfed	8.13 ^{h}	12.69 ^{cdef}	13.12 ^{bcde}	12.51 ^{cdef}	3.96 ^{i}	12.29 ^{defg}	12.91 ^{cde}	11.21 ^{fg}	18.23 ^{a}
	Bean	Irrigated	11.43 ^{bc}	13.51 ^{bc}	14.38 ^{bc}	12.79 ^{bc}	11.64 ^{bc}	14.09 ^{bc}	15.11 ^{bc}	11.96 ^{bc}	36.54 ^{b}
		Rainfed	-140.19 ^{bcd}	2.10 ^{bc}	-19.53 ^{bc}	-560.52 ^{e}	-230.28 ^{d}	-inf ^{bcd}	-152.44 ^{cd}	-276.13 ^{d}	500.80 ^{a}
	Maize	Irrigated	-1.09 ^{a}	-1.08 ^{a}	-0.90 ^{a}	-0.96 ^{a}	-1.87 ^{a}	-1.14 ^{a}	-1.08 ^{a}	-0.71 ^{a}	0.15 ^{a}
		Rainfed	-369.90 ^{abcd}	-44.50 ^{ab}	-144.87 ^{abc}	-1,902.56 ^{e}	-813.00 ^{d}	-527.02 ^{bcd}	-544.91 ^{bcd}	-658.20 ^{cd}	-86.60 ^{ab}
	Soybean	Irrigated	5.78 ^{ef}	6.00 ^{dce}	6.51 ^{bcd}	5.92 ^{def}	4.23 ^{g}	6.59 ^{bc}	7.06 ^{b}	5.46 ^{ef}	7.96 ^{a}
		Rainfed	4.68 ^{g}	4.19 ^{g}	5.36 ^{f}	4.69 ^{g}	2.03 ^{h}	5.70 ^{ef}	5.53 ^{ef}	4.26 ^{g}	5.99 ^{cdef}
Correntina	Cotton	Irrigated	8.22 ^{a}	9.70 ^{a}	8.69 ^{a}	6.71 ^{ab}	3.63 ^{abc}	4.91 ^{abc}	4.27 ^{abc}	5.30 ^{abc}	7.02 ^{ab}
		Rainfed	5.89 ^{abc}	6.34 ^{ab}	7.54 ^{ab}	6.15 ^{abc}	-36.96 ^{d}	-1.15 ^{c}	0.47 ^{bc}	2.51 ^{abc}	6.38 ^{ab}
	Bean	Irrigated	8.22 ^{a}	8.96 ^{a}	8.44 ^{a}	7.48 ^{a}	6.00 ^{a}	6.61 ^{a}	6.31 ^{a}	6.81 ^{a}	7.62 ^{a}
		Rainfed	-21.26 ^{ab}	-783.55 ^{d}	-15.84 ^{ab}	4.26 ^{a}	-108.08 ^{ab}	-173.09 ^{b}	-478.49 ^{c}	-17.01 ^{a}	-44.05 ^{ab}
	Maize	Irrigated	-0.83 ^{a}	-1.14 ^{a}	-0.67 ^{a}	-0.98 ^{a}	-2.20 ^{a}	-2.07 ^{a}	-1.53 ^{a}	-1.45 ^{a}	-0.90 ^{a}
		Rainfed	-86.41 ^{a}	-1,372.40 ^{d}	-177.67 ^{ab}	-27.27 ^{a}	-154.48 ^{a}	-599.08 ^{bc}	-909.30 ^{c}	-49.96 ^{a}	-101.83 ^{a}
	Soybean	Irrigated	4.33 ^{c}	5.00 ^{a}	4.41 ^{bc}	3.46 ^{de}	2.08 ^{j}	2.78 ^{fgh}	2.53 ^{ghi}	2.90 ^{fg}	3.09 ^{ef}
		Rainfed	4.48 ^{bc}	4.47 ^{bc}	4.82 ^{ab}	3.66 ^{d}	0.38 ^{l}	1.63 ^{k}	2.34 ^{ij}	2.36 ^{hij}	3.44 ^{de}
Luís Eduardo Magalhães	Cotton	Irrigated	9.87 ^{fg}	10.86 ^{efg}	10.80 ^{efg}	12.76 ^{cd}	10.02 ^{fg}	11.14 ^{ef}	16.11 ^{a}	13.06 ^{c}	7.96 ^{i}
		Rainfed	7.54 ^{i}	9.60 ^{gh}	9.85 ^{fg}	11.59 ^{de}	2.27 ^{j}	8.42 ^{hi}	14.76 ^{b}	12.59 ^{cd}	7.66 ^{i}
	Bean	Irrigated	9.14 ^{a}	10.01 ^{a}	9.91 ^{a}	10.54 ^{a}	10.07 ^{a}	10.63 ^{a}	13.82 ^{a}	11.39 ^{a}	9.00 ^{a}
		Rainfed	-96.09 ^{ab}	-130.62 ^{b}	-130.24 ^{b}	-369.64 ^{cd}	-460.29 ^{d}	-264.04 ^{c}	-28.77 ^{ab}	-5.51 ^{ab}	-106.24 ^{ab}
	Maize	Irrigated	-1.25 ^{a}	-1.00 ^{a}	-0.87 ^{a}	-0.67 ^{a}	-1.94 ^{a}	-1.40 ^{a}	-0.61 ^{a}	-0.51 ^{a}	-0.71 ^{a}
		Rainfed	-368.85 ^{a}	-316.88 ^{a}	-332.65 ^{a}	-921.57 ^{b}	-1,705.99 ^{c}	-820.49 ^{b}	-104.64 ^{a}	-64.50 ^{a}	-92.87 ^{a}
	Soybean	Irrigated	4.19 ^{e}	4.36 ^{de}	4.19 ^{e}	5.42 ^{b}	4.14 ^{e}	4.76 ^{cd}	7.09 ^{a}	5.40 ^{b}	3.49 ^{fg}
		Rainfed	4.22 ^{e}	4.30 ^{de}	3.96 ^{ef}	5.16 ^{bc}	3.39 ^{g}	3.95 ^{ef}	7.28 ^{a}	5.61 ^{b}	3.51 ^{fg}

2.4.7. Irrigated and rainfed areas equivalence

Table 12 shows the crop rotation models' results of average and maximum gross revenue values for 2016. In Barreiras, the equivalence for one hectare of irrigated area is, on average, 1.67 and 1.98, varying between 1.37 and 2.79 hectares of rainfed areas. In Correntina, the average values are 2.96 and 3.90, with a variation between 1.92 and 12.55 hectares of rainfed. For Luis Eduardo Magalhães, the average values vary between 1.73 and 1.98, with a variation between 1.33 and 2.92 hectares of rainfed.

Table 12 – Average and maximum gross revenue values for the crop rotation model in Barreiras, Correntina, and Luis Eduardo Magalhães for 2016.

County	Crop rotation	Gross revenue ave. (R$/ha)		Gross revenue max. (R$/ha)		IAE ave.	IAV max.
		Irrigated	Rainfed	Irrigated	Rainfed	hectares	hectares
Barreiras	Bean-Maize	12,117	6,022	12,575	8,224	2.01	1.53
	Bean-Cotton	20,156	11,948	20,720	13,742	1.69	1.51
	Bean-Soybean	13,428	7,923	13,912	10,179	1.69	1.37
	Bean-Soybean-Maize	16,961	8,163	17,628	10,288	2.08	1.71
	Maize-Bean	11,947	5,092	12,206	5,979	2.35	2.04
	Cotton-Bean	19,970	11,721	20,615	13,889	1.70	1.48
	Cotton-Maize	17,217	9,600	17,786	12,270	1.79	1.45
	Soybean-Bean	13,279	6,917	13,516	8,254	1.92	1.64
	Soybean-Maize	8,908	4,691	9,040	5,416	1.90	1.67
	Soybean-Maize-Bean	16,250	5,823	17,005	7,257	2.79	2.34
	Soybean-Maize-Cotton	21,449	10,049	22,270	11,764	2.13	1.89
	Soybean-Cotton	18,503	10,941	18,824	12,871	1.69	1.46
	Average values					1.98	1.67
Correntina	Bean-Maize	3,421	273	3,487	487	12.55	7.16
	Bean-Cotton	18,356	7,721	18,740	8,851	2.38	2.12
	Bean-Soybean	12,446	4,870	13,032	6,492	2.56	2.01
	Bean-Soybean-Maize	15,712	4,950	16,354	6,495	3.17	2.52
	Maize-Bean	10,618	1,822	10,794	2,164	5.83	4.99
	Cotton-Bean	18,290	7,484	18,777	8,631	2.44	2.18
	Cotton-Maize	15,992	6,678	16,759	8,631	2.39	1.94
	Soybean-Bean	12,136	3,816	12,440	5,484	3.18	2.27
	Soybean-Maize	8,154	2,914	8,354	3,611	2.80	2.31
	Soybean-Maize-Bean	14,987	3,283	15,626	4,318	4.56	3.62
	Soybean-Maize-Cotton	20,196	7,323	20,888	8,574	2.76	2.44
	Soybean-Cotton	17,241	7,809	17,486	9,115	2.21	1.92
	Average values					3.90	2.96
Luís Eduardo Magalhães	Bean-Maize	12,234	6,615	12,665	8,573	1.85	1.48
	Bean-Cotton	21,298	11,275	21,631	12,661	1.89	1.71
	Bean-Soybean	13,607	8,543	14,055	10,558	1.59	1.33
	Bean-Soybean-Maize	16,898	8,694	17,273	10,652	1.94	1.62
	Maize-Bean	11,791	4,814	11,898	5,546	2.45	2.15
	Cotton-Bean	20,189	12,016	20,738	13,536	1.68	1.53
	Cotton-Maize	17,397	10,207	17,979	12,449	1.70	1.44
	Soybean-Bean	13,237	6,789	13,799	9,031	1.95	1.53
	Soybean-Maize	8,925	4,849	9,030	5,245	1.84	1.72
	Soybean-Maize-Bean	15,827	5,421	16,284	6,049	2.92	2.69
	Soybean-Maize-Cotton	20,988	9,405	21,343	10,162	2.23	2.10
	Soybean-Cotton	18,447	10,936	18,971	13,557	1.69	1.40
	Average values					1.98	1.73

Table 13 shows similar results for 2020. In Barreiras, the equivalence for one hectare of irrigated area is given in average values of 1.04 and 1.17, varying between 1.01 and 1.28 hectares of rainfed areas. The average values of this equivalence for Correntina are 1.47 and 1.69, with a variation between 1.19 and 2.31 hectares of rainfed. For Luis Eduardo Magalhães, the average values vary between 1.29 and 1.38, with a variation between 1.11 and 1.84 hectares of rainfed.

Table 13 - Average and maximum values of gross revenue for crop rotation model, in Barreiras, Correntina and Luis Eduardo Magalhães for the year 2020.

County	Crop rotation	Gross revenue ave. (R$/ha)		Gross revenue max. (R$/ha)		IAE ave.	IAV max.
		Irrigated	Rainfed	Irrigated	Rainfed	hectares	hectares
Barreiras	Bean-Maize	13,424	11,099	14,016	13,830	1.21	1.01
	Bean-Cotton	23,391	21,325	23,837	23,630	1.10	1.01
	Bean-Soybean	14,503	12,210	15,199	15,032	1.19	1.01
	Bean-Soybean-Maize	18,622	14,940	19,398	17,758	1.25	1.09
	Maize-Bean	13,826	12,393	13,989	13,580	1.12	1.03
	Cotton-Bean	22,838	19,443	23,503	22,894	1.17	1.03
	Cotton-Maize	18,519	14,476	19,189	18,222	1.28	1.05
	Soybean-Bean	14,949	13,701	15,100	14,830	1.09	1.02
	Soybean-Maize	9,955	8,709	10,116	9,917	1.14	1.02
	Soybean-Maize-Bean	18,617	15,597	19,078	17,256	1.19	1.11
	Soybean-Maize-Cotton	24,035	19,875	24,411	21,673	1.21	1.13
	Soybean-Cotton	20,442	19,115	20,682	20,096	1.07	1.03
	Average values					1.17	1.04
Correntina	Bean-Maize	12,088	6,803	12,285	8,357	1.78	1.47
	Bean-Cotton	20,690	14,208	21,088	15,749	1.46	1.34
	Bean-Soybean	13,359	8,547	13,699	10,371	1.56	1.32
	Bean-Soybean-Maize	16,654	8,778	17,027	10,646	1.90	1.60
	Maize-Bean	12,161	6,959	12,546	9,566	1.75	1.31
	Cotton-Bean	20,414	13,545	20,901	14,988	1.51	1.39
	Cotton-Maize	17,076	10,294	17,476	11,718	1.66	1.49
	Soybean-Bean	13,511	9,129	13,983	11,282	1.48	1.24
	Soybean-Maize	8,991	5,768	9,156	6,633	1.56	1.38
	Soybean-Maize-Bean	16,057	6,960	16,411	7,810	2.31	2.10
	Soybean-Maize-Cotton	21,200	11,088	21,447	11,756	1.91	1.82
	Soybean-Cotton	18,811	13,566	19,280	16,194	1.39	1.19
	Average values					1.69	1.47
Luís Eduardo Magalhães	Bean-Maize	13,092	9,602	13,537	10,819	1.36	1.25
	Bean-Cotton	22,469	18,368	23,083	19,919	1.22	1.16
	Bean-Soybean	14,284	11,189	14,871	12,866	1.28	1.16
	Bean-Soybean-Maize	17,811	11,663	18,412	13,540	1.53	1.36
	Maize-Bean	13,207	9,834	13,775	11,300	1.34	1.22
	Cotton-Bean	22,141	17,325	22,472	18,688	1.28	1.20
	Cotton-Maize	18,216	13,058	18,562	14,922	1.39	1.24
	Soybean-Bean	14,521	11,956	15,038	13,116	1.21	1.15
	Soybean-Maize	9,690	7,566	9,865	8,293	1.28	1.19
	Soybean-Maize-Bean	17,283	9,382	17,606	9,705	1.84	1.81
	Soybean-Maize-Cotton	22,433	13,648	22,756	14,002	1.64	1.63
	Soybean-Cotton	19,930	16,711	20,503	18,501	1.19	1.11
	Average values					1.38	1.29

Results show that the equivalence between irrigated and rainfed areas is considerably greater in years of reduced rainfall such as 2016 than in years of suitable climatic conditions as 2020. Still, even in these wet years, the potential for generating income in irrigated areas is considerably larger than in rainfed conditions.

2.4.8. Gross revenue increase by adjusting planting dates

Considering only the best crop’s planting dates in irrigated areas, the potential for generating gross revenue from crop rotation models increases by 3% on average for 2016 and 2020. For rainfed areas, greater increases are observed in 2016, with an average of 22% for Barreiras, 30% for Correntina, and 19% for Luís Eduardo Magalhães. In 2020, the increments are 15%, 18%, and 10%, respectively. The complete results of this analysis can be seen in Table 14.

Table 14 – Gross revenue increase for crop rotation model, in Barreiras, Correntina, and Luis Eduardo Magalhães for 2016 and 2020.

County	Crop rotation	2016		2020	
		Irrigated (%)	Rainfed (%)	Irrigated (%)	Rainfed (%)
Barreiras	Bean-Maize	3.77%	36.56%	4.41%	24.61%
	Bean-Cotton	2.80%	15.01%	1.91%	10.81%
	Bean-Soybean	3.60%	28.48%	4.80%	23.12%
	Bean-Soybean-Maize	3.94%	26.04%	4.17%	18.86%
	Maize-Bean	2.17%	17.42%	1.18%	9.58%
	Cotton-Bean	3.23%	18.49%	2.91%	17.75%
	Cotton-Maize	3.31%	27.80%	3.62%	25.87%
	Soybean-Bean	1.78%	19.32%	1.01%	8.24%
	Soybean-Maize	1.49%	15.46%	1.62%	13.86%
	Soybean-Maize-Bean	4.65%	24.63%	2.48%	10.64%
	Soybean-Maize-Cotton	3.83%	17.06%	1.57%	9.05%
	Soybean-Cotton	1.74%	17.64%	1.17%	5.13%
	Average values	3.03%	21.99%	2.57%	14.79%
Correntina	Bean-Maize	1.93%	78.60%	1.63%	22.85%
	Bean-Cotton	2.09%	14.64%	1.92%	10.84%
	Bean-Soybean	4.71%	33.31%	2.54%	21.34%
	Bean-Soybean-Maize	4.09%	31.20%	2.24%	21.28%
	Maize-Bean	1.66%	18.76%	3.17%	37.46%
	Cotton-Bean	2.66%	15.32%	2.39%	10.66%
	Cotton-Maize	4.79%	29.25%	2.34%	13.83%
	Soybean-Bean	2.50%	43.72%	3.49%	23.58%
	Soybean-Maize	2.45%	23.91%	1.83%	14.99%
	Soybean-Maize-Bean	4.26%	31.52%	2.20%	12.22%
	Soybean-Maize-Cotton	3.43%	17.07%	1.16%	6.03%
	Soybean-Cotton	1.42%	16.72%	2.49%	19.37%
	Average values	3.00%	29.50%	2.28%	17.87%
Luís Eduardo Magalhães	Bean-Maize	3.52%	29.60%	3.40%	12.67%
	Bean-Cotton	1.56%	12.29%	2.73%	8.44%
	Bean-Soybean	3.29%	23.58%	4.11%	14.99%
	Bean-Soybean-Maize	2.22%	22.52%	3.37%	16.09%
	Maize-Bean	0.91%	15.20%	4.30%	14.91%
	Cotton-Bean	2.71%	12.65%	1.49%	7.87%
	Cotton-Maize	3.34%	21.97%	1.90%	14.28%
	Soybean-Bean	4.24%	33.04%	3.56%	9.70%
	Soybean-Maize	1.18%	8.17%	1.81%	9.60%
	Soybean-Maize-Bean	2.89%	11.60%	1.87%	3.44%
	Soybean-Maize-Cotton	1.69%	8.05%	1.44%	2.59%
	Soybean-Cotton	2.84%	23.96%	2.88%	10.71%
	Average values	2.53%	18.55%	2.74%	10.44%

2.5. DISCUSSION

This study demonstrates that irrigated areas typically present higher values of crop yields, gross profit, and water profitability and lower values of water productivity compared to rainfed areas.

From Figures 22, 23, 24, 25, there is a marked water deficit, especially in crops traditionally cultivated as a second crop, resulting in yield losses. This result is compatible with that described by Abrahão and Costa (2018), where rainfall conditions mostly affect the second crop in double-cropping systems. Crop yields and water productivity, except for conditions with large crop failures, are also compatible with those determined by Flach *et al.* (2020).

The equivalence between irrigated and rainfed areas can be even greater than that presented in Table 9, particularly because, in this study, perennial crops of greater added value such as coffee and oranges, which are typically irrigated, were not considered. As shown in Table 14, the information on the beginning of the rainy season can cause significant increases in productivity, especially in rainfed conditions.

The rainy season onset forecast is also of great importance for irrigated areas. Water availability is typically defined in months of low water availability, directing governance actions to avoid water use conflicts.

A possible improvement of this study is the inclusion of the actual precipitation forecast values to improve the computation of water productivity and water profitability.

2.6. CONCLUSIONS

This work aimed to demonstrate economic indicators that describe irrigated agriculture compared to rainfed agriculture in Western Bahia and the possible increases given the adoption of the rainy season onset forecast for the region. The main results show that the irrigated areas can be equivalent to 1.69 to 3.90 hectares of rainfed on average. When the correct decision for the crops planting date was adopted, farmers potentially achieve considerable gains in gross revenue in the range of 3% for irrigated areas and 10 to 30% for rainfed areas.

2.7. REFERENCES

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